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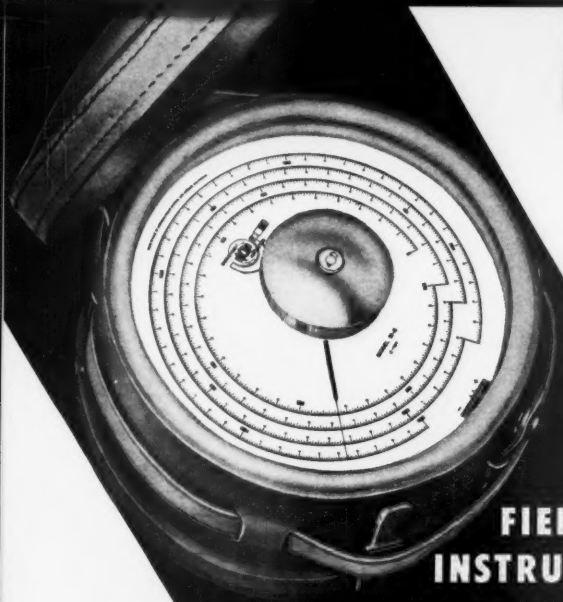

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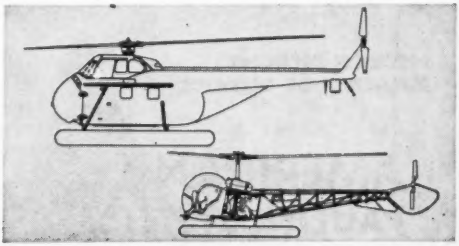

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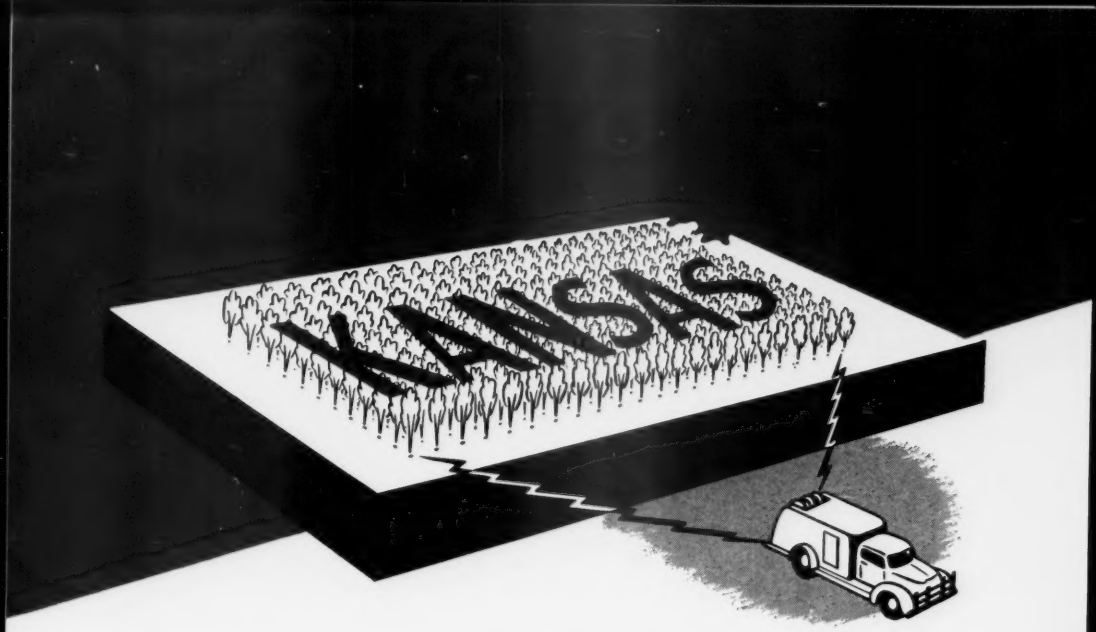

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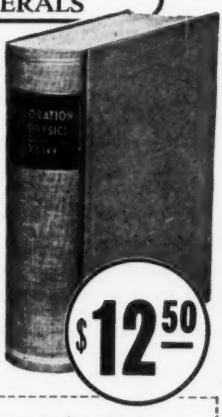

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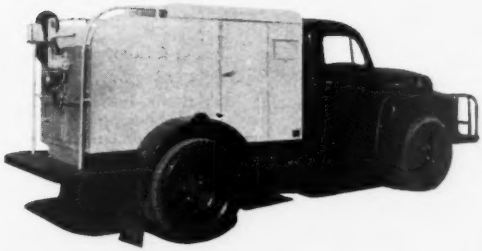

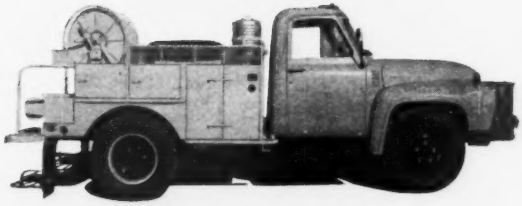

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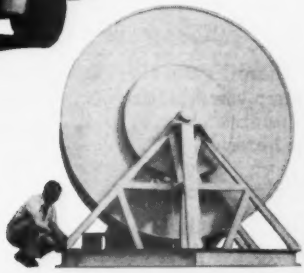

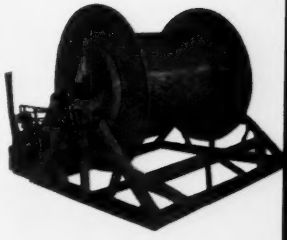

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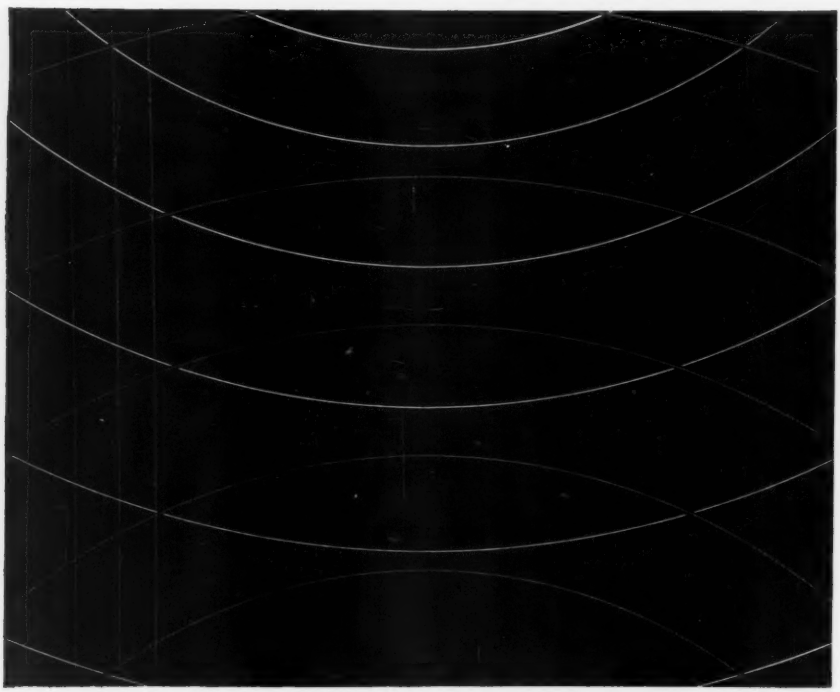

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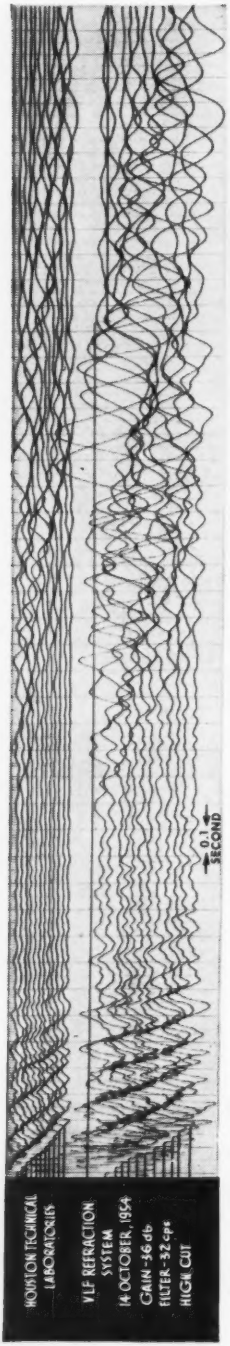

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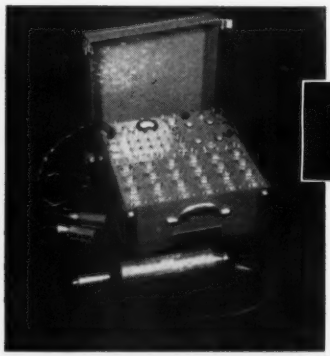

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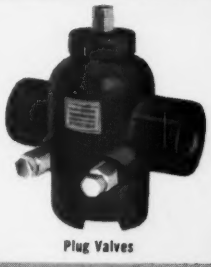

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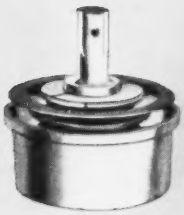

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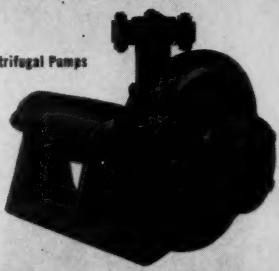

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VOLUME XXI JULY, 1956 NUMBER 3

GEOPHYSICS

ANTARCTIC RESEARCH IN CONNECTION WITH THE INTERNATIONAL GEOPHYSICAL YEAR*

HARRY WEXLER†

ABSTRACT

During 1957–58 a dozen nations will establish thirty-five geophysical stations in Antarctica. Thus, this continent, whose area is larger than that of the United States and Mexico combined, will be the subject of concentrated, coordinated geophysical exploration, to a degree not dreamed possible a few years ago. For the first time geophysical stations will be established away from the coasts, deep in the interior of the continent. Scientists from the various nations will cooperate in exploring the temperatures, winds and electrical properties of an atmosphere cut off from sunlight for many months. The thickness of the ice will be surveyed and examined for indications of increase or decrease of its volume over the years, to see if Antarctic climate is changing. The Aurora Australis will be photographed and compared with its Northern Hemisphere counterpart, the Aurora Borealis. Intensive measurements will be made of geomagnetism, cosmic rays, airglow, and the ionosphere in an attempt to throw light on the physics of the high atmosphere.

In early November of 1956 a group of 95 geophysicists will depart from the United States for a scientific exploration of the Antarctic. These scientists will perform measurements and surveys in a coordinated effort of unprecedented magnitude, the International Geophysical Year of 1957–58. Fifty-five nations have expressed a willingness to participate in this great enterprise. Eleven of these nations will join in the assault on the geophysical secrets of Antarctica, the fifth largest continent—whose topography is less known than that of the visible surface of the moon. Approximately 39 observing stations are planned on the Antarctic continent, with additional stations in the sub-Antarctic. During periods of maximum activity, the population of Antarctica—an area usually uninhabited—will rise to five or six thousand. All details of the operations of some of the countries are not available; but perhaps 50 ships, and as many aircraft, may be assigned to Antarctic operations, and the number of motor-driven vehicles may reach two hundred or more.

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All this activity will appear strange in a continent which was first seen by man in 1820, and whose interior was first explored in the period 1898 to 1916 by such giants as Amundsen, Scott, and Shackleton. The modern phase of exploration began with the first Byrd Expedition of 1928 and since that date many nations have landed expeditions using more modern surface vehicles and aircraft. Valuable meteorological and other geophysical observations have been taken at scattered stations over the years but not in sufficient detail to do more than to reveal the existence of puzzling geophysical features, such as the unusually persistent low barometric pressure observed in the Little America area—about one inch of mercury below that found elsewhere in the world.

The new effort with marked emphasis on the geophysics of the Antarctic is to take place during the period from July 1, 1957 to December 31, 1958 when the world's geophysicists will make a coordinated, concentrated study aimed at a better understanding of the earth and its star, the sun. Although the most ambitious program in international scientific cooperation ever attempted, the IGY is not the first venture of its kind. In 1882–83, and 50 years later, in 1932–33, there were the First and Second International Polar Years in which several nations cooperated to explore the atmosphere of the Arctic. The historical accounts contain unbelievable stories of peril and hardship; but the resulting contributions to our knowledge of Arctic meteorology, geomagnetism, and the aurora are still referred to today. As an example of the value of such effort, the ionospheric information alone acquired during the Second Polar Year is estimated to have contributed information worth 10 billion dollars to the field of radio communications.

During the coming International Year, the adjective "Geophysical" is substituted for "Polar" because of the emphasis on the study of the earth as a whole. Scientists will work in these fields:

Aurora and airglow
Cosmic rays
Earth satellite program
Geomagnetism
Glaciology
Gravity
Ionospheric physics
Latitude and longitude
Meteorology
Oceanography
Rocket exploration of the upper atmosphere
Seismology
Solar activity

Emphasis is being given to filling gaps in global networks and establishing several meridional lines of stations from Pole to Pole. There will also be both World Days and World Meteorological Intervals at times of unusual solar and geophysical interest. A warning service will alert all fields by broadcasting to the world the onset or presence of solar flares, magnetic storms, ionospheric fade-outs, etc., so that observers can proceed with pre-arranged studies of a more concentrated type than are carried out even during an International Geophysical Year.

The scheduling of the third International Year, coming 25 instead of 50 years after the second, was influenced by the anticipated increase in solar activity, as characterized by sunspots, expected during 1957–58 and by the rapid advances in instrumental techniques and research vehicle development such as is found in present day observations with balloons, aircraft, and rockets.

Such a global undertaking, coming along only once every generation or two, requires careful planning and coordination to get the most out of the observations. In the present case planning started shortly after the idea was suggested by a group of American geophysicists in early 1950. Three large international congresses have already been held, together with several smaller specialized ones, to formulate plans, to coordinate efforts, and to exchange information. The 43 nations which have announced definite programs will spend close to $250,000,000 on the program.

Two planning conferences for the Antarctic phase of the IGY, held in Paris last July and in Brussels in September were attended by representatives of the United States, the USSR, Great Britain, France, Norway, Australia, New Zealand, Argentina, Chile, the Union of South Africa, and Japan. Spain may also join in the undertaking. The meetings were held in an atmosphere of good will, with attention focused on the scientific programs and the location of the proposed stations. Some of the nations willingly transferred their planned stations to new sites to fill large gaps in the observing network, and all nations agreed to exchange freely all information on logistics and scientific matters.

In Fig. 1 the proposed station locations are shown on a map of Antarctica. The seven U. S. stations, identified by stars, cover one-half of the continent from the Weddell Sea westward to Marie Byrd Land, Little America, the Ross Sea, and the Knox Coast. One of these stations, Cape Adare, will be operated jointly by New Zealand and the U. S. New Zealand will also have a station at McMurdo Sound at which most of the scientific measurements in that area will be taken. The U. S. will have a nearby air support facility to furnish air lift to and from Antarctica and aid in the establishment of the U. S. scientific station at the geographic South Pole.

Stations proposed by other nations are also shown. The USSR plans three stations, one at the Knox Coast to the west of the U. S. base, and two inland—one at the South Geomagnetic Pole and the third in the center of the continent, known as the Pole of Inaccessibility. A few months ago our planes flew over this territory and found a high snow-covered plateau, perhaps 13,000 feet in altitude.

The French station at Adelie Land between the Cape Adare and the U. S. Knox stations will have a satellite station a few hundred miles inland, near the South Magnetic Pole. The Australians have had their Mawson station established on the coast of Enderby Land for two years and have recently made a reconnaissance to open up a new station at Vestfold Hills, a few hundred miles to the east.

The Japanese will enter actively into Antarctic work for the first time since 1912 when Lieutenant Choku Shirase discovered Kainan and Okuma Bays. Kainan Bay is now used as a harbor to supply the present U. S., Little America V station located three miles to the south. The Japanese have volunteered to fill an important gap on the Prince Harald Coast between Mawson and the Norwegian Station to be located near Maudheim, site of the joint Norwegian-British-Swedish Expedition of 1949–52. On the Weddell Sea the Argentines, British, and

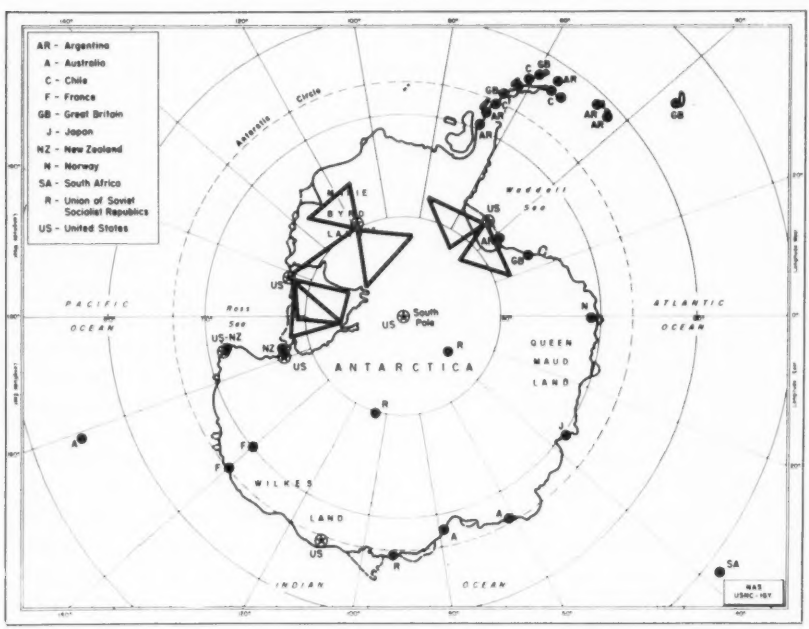

FIG. 1. Planned U. S. and foreign Antarctic Stations and glaciological traverses.

Americans will each have a station. The U. S. will attempt to penetrate far west, to the foot of the Palmer Peninsula, if ice conditions permit.

The Palmer Peninsula already has a dense network of stations, established by Argentina, Chile, and Great Britain; but most of these emphasize surface meteorological observations.

At the U. S. stations there will be scientific programs in meteorology, aurora and airglow, ionospheric physics, geomagnetism, cosmic rays, seismology, gravity measurements, and glaciology, carried out under the over-all direction of Dr. L. M. Gould, Chairman of the USNC-IGY Antarctic Committee and Second-in-Command of the 1928–30 Byrd Expedition. Rear Admiral Richard

E. Byrd is in over-all charge of the Department of Defense supporting activity and Rear Admiral George Dufek is the Commander of Task Force 43, which is charged with the detailed expeditionary and logistics tasks.

The US-IGY Antarctic Program really started in November 1954 when the USS ATKA, an ice-breaker just back from the Arctic, left on a mission to reconnoiter possible bases for the later expeditions. They found that the ice forming the famous Bay of Whales, harbor for the previous U. S. expeditions had broken off, necessitating the choice of Kainan Bay for further mooring and unloading operations. In addition to this reconnaissance work, so necessary for the later establishment of the IGY base, scientists aboard the ATKA performed valuable experiments in cosmic rays, oceanography, meteorology, and ionospheric physics. For example, the cosmic ray measurements on the ATKA showed that above the atmosphere the earth's magnetic field is tilted from the magnetic equator more than was formerly believed. The measurements of carbon dioxide in the Antarctic air showed values much lower than those measured during the U. S. 1939–41 Expedition. Ionospheric measurements were attempted to confirm theories regarding "whistlers," an audio frequency radio disturbance which is initiated by a lightning flash and which is propagated along a magnetic line of force several thousand miles outside the earth's atmosphere and back to earth in the opposite polar hemisphere.

The main bulk of the building construction material, living supplies, and scientific equipment was shipped last November as part of the Navy operation known as DEEPFREEZE I. Over 9,000 tons of cargo valued in excess of $10,000,000 was unloaded under difficult circumstances at Kainan Bay and at Hut Point in McMurdo Sound. The thin-skinned cargo ships in several instances could not safely penetrate the ice and had to transfer their cargo to the sturdier ice-breakers to avoid damage. Then transfer was made to hugh tractor-pulled sledges for movement to the camp sites. The cargo included material not only for the Little America V and the McMurdo Sound stations but also for the Byrd Land and South Pole stations. The Byrd Land Station will be established by tractor trains. More than half of the route to this station, which passes through some heavily crevassed areas, was surveyed by a trail party with caterpillar-treaded vehicles before operations ceased in early February. The South Pole Station will be established by air lift using USAF planes to drop the supplies and in some cases to land on the 9,000 foot high polar plateau, if landing conditions are satisfactory. These two stations are especially valuable because permanent, or semi-permanent, stations have never been situated so far inland from the Coast, that is, more than 200 miles. Of all the other nations only the USSR will follow the initiative of the United States in this respect.

The location for the Byrd Land Station at 80° S. and 120° W. was chosen because previous scanty meteorological observations dating back to the Scott Expedition of 1912, indicated that this point is near the source of rather mysterious barometric pressure waves and surges which apparently radiate outwards

like waves in a pond after a stone has been thrown in. These waves are thought by some meteorologists to affect the weather in the Southern Hemisphere and perhaps in the Northern Hemisphere. Also, the auroral zone is believed to pass over this location.

The South Pole Station was chosen for the prime purpose of observing the behavior of an atmosphere cut off from sunlight for the better part of six months. Since the ionosphere owes its existence to solar ultraviolet rays it will be fascinating to see if a normal ionosphere is found in the winter darkness over the South Pole.

Unusually low atmospheric temperatures, dropping to perhaps −120°F. at the surface have no counterpart at the North Pole where the air acquires heat by conduction through the ice pack from the warm ocean beneath. The sharp distinction between troposphere and stratosphere found elsewhere probably vanishes in the Antarctic night since the temperature of the lower atmosphere can drop to values nearly as low as those found in the stratosphere. Illustrating this, Fig. 2 shows winter and summer vertical temperature profiles made at Maudheim by the Norwegian-British-Swedish expedition five years ago (Schumacher, 1955).

All of the Antarctic stations will have self-tracking radiosonde equipment to obtain upper winds along with temperature, pressure, and humidity data. Balloons with radiosondes will be launched twice daily and many of the soundings are expected to reach 100,000 feet. In addition to the usual meteorological observations made at a surface station there will be measurements of heat flux, solar radiation, surface albedo, and of total ozone. There will also be specialized equipment such as the infrared hygrometer for recording humidity under very cold conditions.

During the IGY and for the first time in the Antarctic, there will be sufficient meteorological stations to permit the drawing of a surface weather map based on actual observations. More exciting yet is the probability that upper air charts can be prepared from the reports of the stations in the Antarctic network. At the request of the International Geophysical Year Committee, the United States has agreed to assume the responsibility for an Antarctic Weather Central at the main IGY camp at Little America V to collect and relay observations from all stations including those of other nations, and to prepare weather analyses and forecasts for all Antarctic operations as required.

Because of the interest of meteorologists, glaciologists, and oceanographers in the chemical constituents of the air, the ice, and the ocean water, steps are being taken to establish a small chemical laboratory at Little America with a geochemist working full-time. Such a chemist would make measurements of oxygen, carbon dioxide, surface ozone, and water vapor. If it is possible to install and operate such equipment as a small mass spectrometer then he would also measure isotope ratios of gases such as oxygen.

All Antarctic stations will observe the mysterious Aurora Australis to see if

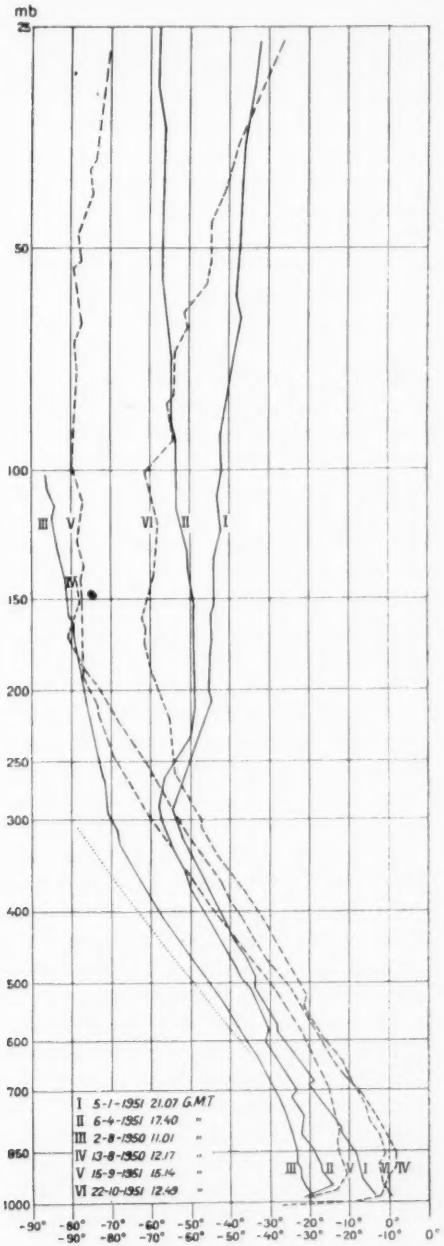

FIG. 2. Selected temperature soundings from Maudheim, Queen Maud Land, Antarctica. Vertical scale is atmospheric pressure in millibars. Bottom scale is temperature in degrees Centigrade; full lines refer to the upper temperature scale; dashed lines to the lower temperature scale. Dotted line is a dry adiabat (after Schumacher (1955)).

these bright streamers and luminous waving curtains occur simultaneously with its Northern Hemisphere counterpart—the Aurora Borealis. Both auroral systems are formed by atoms and electrons streaming from the sun, converging toward the earth's magnetic poles and exciting the gases in the atmosphere. The more subdued optical effect caused by solar radiation called the airglow will also be studied during the long winter night.

Before closing this discussion of the IGY Antarctic program, I would like to give an account of a subject which you, as members of a profession which relies so heavily on seismic techniques, should find most interesting. I refer to the glaciological program planned for study of Antarctic ice. Glaciers now cover 10 percent, or 6,000,000 square miles of the earth's land area. The Antarctic Ice Sheet accounts for 86 percent of this glacial area, and the Greenland Ice Cap for another 10 percent. The estimates of the volume of water entrapped in the world's glaciers range from 6.3 to 8.7 million cubic miles. If all this ice were melted, it would raise the level of the oceans by 140 to 200 feet, even after allowance is made for isostatic adjustments.

The degree of uncertainty in the above figures is due largely to ignorance of the volume of ice in Antarctica. The amount of ice is estimated by seismic soundings of ice depth along various lines such as shown in Fig. 3, which gives the route of the main seismic journey out of Maudheim from October 1951 to January 1952. Ice thickness measurements were made under direction of the British physicist G. de Q. Robin (Robin, 1953), using six seismometers normally spaced 33 feet apart in line with and separated from the shot point by distances of 30 to 600 feet depending on ice thickness. The shots consisted of TNT charges ranging from $\frac{1}{5}$ to $1\frac{1}{2}$ pounds that were placed in hand-bored holes from 6 to 40 feet deep. Amplifier band pass filters were normally set at 90 cycles per second. Corrections to ice depths to allow for slower velocities in the surface layers were based on shots fired at the bottom of a bore hole more than 300 feet deep at Maudheim, and varied from about 60 to 130 feet. However, from independent checks elsewhere accuracy of 5 percent was claimed. The ice depths were determined by reflection of the longitudinal P wave travelling approximately 12,500 feet per second, the velocities determined in the field by refraction shooting techniques. The absolute height above sea-level was determined by three aneroid barometers. The results are shown in Fig. 4 where vertical strokes above the horizontal distance scale indicate points at which seismic soundings were made.

The Ice Shelf thickness at Maudheim is about 610 feet, with more than a thousand feet of ocean beneath. Over islands, the ice forms into rounded hills principally by the mechanism of flow rather than because of the underlying relief. Going inland from 100 to 300 miles, the bottom relief changes to an alpine type covered by ice a mile thick. Snow collapses induced by the explosions interfered with accurate depth determinations farther inland and the relief is certainly much more rugged than that shown. The maximum ice depth found was $1\frac{2}{3}$ miles. If the equivalent of 10 inches of ice is precipitated per year on the inland plateau, then the age of the bottom ice would be over 10,000 years.

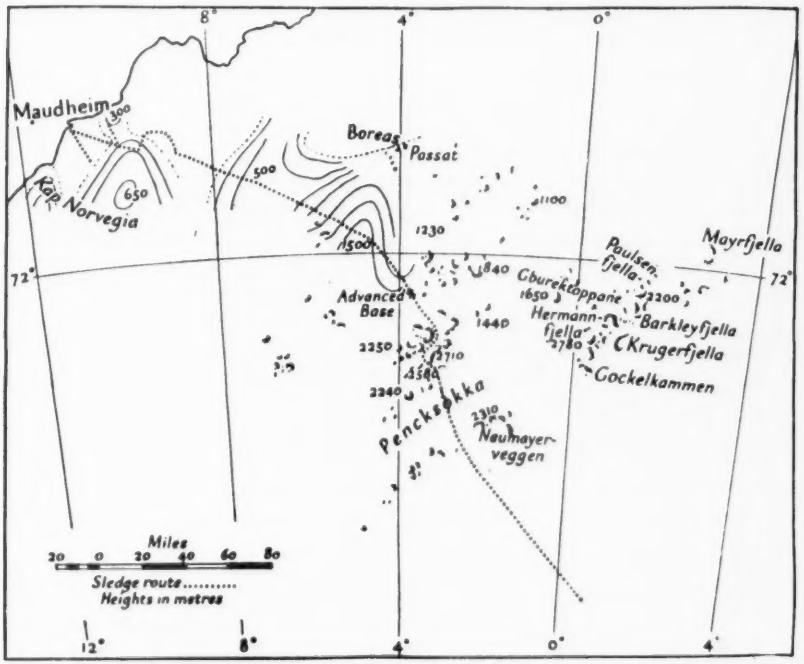

FIG. 3. The route of the main seismic journey out of Maudheim (after Robin (1952)).

Pooling together the ice depth profiles from glaciological surveys made by the various nations during the IGY will enable a better estimate to be made of the amount of ice stored in the enormous Antarctic ice-house. Mr. A. P. Crary (who is well known to many of you) is organizing and will lead the U. S. Antarctic glaciologic-seismic-gravimetric program. The glaciological traverses planned by the United States are shown in Fig. 1. These journeys will be made during the brief Antarctic spring and early summer with the aid of snow tractors. Light aircraft will be used to guide the ground parties around heavily crevassed areas. In addition to seismic soundings, gravity measurements will also be made to

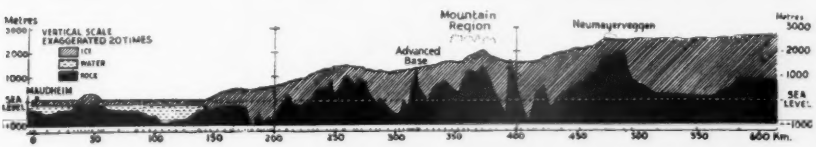

FIG. 4. The main seismic profile showing the ice and rock profiles along the route shown in Fig. 3. The vertical strokes above the distance scale indicate points at which seismic soundings were made (after Robin (1952)).

determine warping of the earth's crust as a function of the growth or decline of the ice sheets. Particular attention will be paid to "nunataks," or bare mountain peaks that stick up above the ice, to see whether they show glacial scratches and lichens. The Norwegian-British-Swedish glaciologists found some ice-scratched nunataks with lichens extending to the present ice surface indicating that the ice level had not lowered within the past half century or so.

If this result is typical of inland ice throughout Antarctica, this would be in surprising contradiction to the declining Arctic Ice Pack which in the past half century has diminished by 40 percent in thickness and by more than 12 percent in horizontal area. If it turns out that the two polar regions move oppositely in the growth or decline of their respective ice volumes, this will indeed give food for thought to those interested in explaining climatic changes.

Antarctica holds exciting prospects for the exploration geophysicist. The continent was once warm, for it contains one of the largest coal reserves in the world—though that which has been found is of poor grade. Next to nothing is known of the useful minerals and oil there. Although we do not go to the Antarctic as prospectors, the IGY program will undoubtedly bring nearer the day when Antarctica will begin to yield its geological treasures. Who can say what the Antarctic will be like in the Age of the Atom with prospects of practically unlimited heat or energy for ships, aircraft, camps, or machines.

The already tested techniques of the exploration geophysicist will be much in use during the IGY. However, the Antarctic offers new challenges. In particular we would like to obtain core samples from deep in the glacial ice and from the rock structure beneath. Consider, if you will, a drilling operation on packed snow, under frequent blizzard conditions at 40 below, to reach down through ice one or two miles thick and recover samples for studies of the crystal structure, foreign material such as pollen, volcanic ash, meteoric particles, and various isotopic components for age determination. There is still ample opportunity to fit this into our US-IGY program if some of you experts with your drilling rigs feel you can meet the challenge! Present plans call for drilling to only 1,000 feet.

I come now to the end of this brief synopsis of Antarctic geophysical research planned during the IGY. The planning phase, combining the labor of dozens of scientists and logistic experts is over; the field phase will begin in November when the main U. S. scientific party of 95 volunteers departs for Antarctica. The placing of these highly trained men safely in the proper place at the proper time together with their sensitive equipment is a task which the Department of Defense, particularly the Navy, has assumed wholeheartedly and whose personnel deserve the gratitude of all of us connected with the IGY program.

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GEOPHYSICS VOL. XXI, NO. 3 (JULY, 1956), PP. 691–714, 5 FIGS., 6 PLATES

SEISMIC WAVE PROPAGATION IN POROUS GRANULAR MEDIA*

NORMAN R. PATERSON†

ABSTRACT

Theoretical and experimental studies have been made of the manner in which sound waves are propagated in porous granular aggregates. A cylindrical piezo-electric source is used and this simulates the explosion of a charge in a seismic shot-hole.

It is found that in general two waves of volume expansion are propagated and that these involve coupled displacements of both constituents of the media. The waves are termed frame-waves, air-waves or liquid-waves depending upon the nature of the pore-filler and the relative displacements of the constituents.

The frame-wave velocity is dependent upon the strength of the frame, the densities of solid and pore-filling materials and the texture of the medium. Air- and liquid-wave velocities are related to the texture of the medium and to the density and viscosity of the pore-filler. Frame-strength is important to a lesser degree. Waves are dispersive only in the case of media of very low permeability.

Attenuation is related to viscosity, texture and frequency. Scattering is probably important only at the highest frequencies and largest particle diameters used in the experiments.

It is shown that porosity and permeability of a beach sand can be inferred from velocity measurements. These properties provide information regarding grain-size, sorting and the nature of the pore-filler.

INTRODUCTION

The work described in this paper was carried out in an attempt to relate elastic wave-velocities in sedimentary formations to the physical and geological properties of the formations.

The many uses of velocity information are described fully in the literature (e.g., Krumbein, 1951). The author (1954) describes some of these and distinguishes three methods of studying velocities which are influenced by the particular use to which the information is to be put. The methods may be described as analytical, statistical and theoretical.

The analytical approach involves the measurement of velocities in samples of the actual geological formation. This may be done in the laboratory, or in the field by velocity logging. The method is that used by Birch, Bancroft, Zisman, Ide, Hughes, West, Richards and others.

In the statistical approach, for which Faust's work is notable, large numbers of field data are related on paper to the known geological parameters of the formations. Thus relations are established which allow prediction of velocity without knowing anything about the mechanism of propagation.

The theoretical approach considers a simplified model of the formation and develops a theory for it. The theory is tested for the model and also for the formation. Suitable modifications of the model are then made. This process,

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† University of Toronto, Canada.

which is one of synthesis, was used by the author in the research described here.

The following aspects of the work are summarized in this paper:

(1) The theories applying to elastic wave propagation in porous granular media.
(2) The experimental technique adopted by the author.
(3) The results of some experiments on un-consolidated quartz sands and glass beads, and comparison with the theory.
(4) The application to the problem of a beach sand.
(5) Summary and conclusions.

DEFINITIONS AND ASSUMPTIONS

A "porous medium" defines a medium composed of two constituents, one solid, one liquid or gas.

The "framework" or "frame" is that part of a porous medium which would remain if the pore-filler were removed. It is the fabric of the medium. It has the spatial dimensions of the medium as a whole but the mass of the solid material.

"Porosity" is the ratio of the volume of the pore-filler to the total volume of the medium.

The notation is similar to that of Gassman (1950a). Superscripts $\wedge$, $\sim$ and $-$ apply to solid material, pore-filler and framework respectively. Symbols appearing without superscripts apply to the medium as a whole or are otherwise self-evident.

The following symbols are defined:

P = pressure in dynes/cm^2.
p = changes in pressure in dynes/cm^2.
$\boldsymbol{p}$ = vector changes in stress in dynes/cm^2.
$\mathbf{s}$ = vector displacement in cms.
$\boldsymbol{e}$ = vector strain in cms/cm.
ρ = density in gms/cm^3.
K = bulk modulus in dynes/cm^2.
μ = modulus of rigidity in dynes/cm^2.
ν = Poisson's ratio.
M = "specific stiffness" or "volume compression modulus" in dynes/cm^2 $= K+4/3\mu$
C_{ij} = elastic constants of anisotropic medium in dynes/cm^2.
c, c_i = wave-speed in cms/sec.
v = particle velocity or velocity of volume displacement, as defined in the text, in cms^3/sec.
n = porosity.
η = viscosity in poises.
ω = angular velocity in radians/sec.
$\boldsymbol{K}$ = directional permeability in cm^2.

Two assumptions are made in this paper and these may be shown to be valid for the conditions of the experiments. Firstly, the media are assumed to be homogeneous in the horizontal plane. Secondly, the wave-length is assumed to be large in comparison with the grain-size. The first ensures that the medium simulates a horizontally stratified earth. Through the second and by means of Rayleigh's theory, we can ignore the effects of scattering.

THEORY

The wave-equations for the propagation of elastic waves in a solid medium may be derived through the substitution in the equations of motion of the medium relations between the stresses and the strains.

Thus the equations of motion

$$\operatorname{div} \boldsymbol{p} = \rho \frac{\partial^2 \mathbf{s}}{\partial t^2} \tag{1}$$

upon substitution of Hooke's law for an isotropic body

$$\left.\begin{aligned} p_i &= -\sum_{j=1}^{6} C_{ij} e_{ij} \\ C_{11} &= C_{22} = C_{33} = K + 4/3\mu \\ C_{12} &= C_{13} = C_{14} = K - 4/3\mu \\ C_{44} &= C_{55} = C_{66} = \mu \\ \text{all other } C_{ij} &= 0 \end{aligned}\right\} \tag{2}$$

yield the wave-equations

$$\left.\begin{aligned} M\nabla^2\theta &= \rho \frac{\partial^2 \theta}{\partial t^2} \\ \mu\nabla^2\boldsymbol{\omega} &= \rho \frac{\partial^2 \boldsymbol{\omega}}{\partial t^2} \end{aligned}\right\} \tag{3}$$

where θ represents the "cubical dilatation," div s, and $\boldsymbol{\omega}$ the "rotation," curl s.

In employing this type of theory it is necessary to keep in mind two facts. Firstly, the ρ of equation (1) is the mass per unit volume of the medium *accelerated* by the stress $\boldsymbol{p}$. Secondly, the C_{ij} of equation (2) is the ratio of a stress to a *corresponding* strain. In a porous medium the following difficulties arise:

(1) *Inertia*

The degree of "coupling" between the two constituents of the medium affects the inertia of the medium. In a strongly coupled medium both constituents are displaced in phase and the effective density is that of the medium as a whole;

$$= \bar{\rho} + n\tilde{\rho}. \tag{4}$$

In a weakly coupled medium the constituents do not move in phase. It is necessary to replace (1) by two equations expressing the motion of the two constituents under their appropriate stresses.

(2) *Viscosity*

A result of imperfect coupling is differential movement of the two constituents with the consequent appearance of a viscous force $\pm\sigma(\bar{v}-\tilde{v})$, where σ is a "specific flow resistance."

(3) *Texture*

As a further result of imperfect coupling, the pore-filler is caused to flow through the pores of the medium. Since the direction of flow is generally different to that of the accelerating pressure-gradient, the inertia of the pore-filler is increased, the effective density become $k\rho$, where k is a "structure factor" depending upon the texture of the medium.

(4) *Elasticity*

The elastic constants of a porous medium are in general functions of the constants of both constituents and the framework. Gassman (1950a) has shown that in a perfectly coupled ("closed") isotropic medium, the elasticity is given by:

$$\left.\begin{aligned} K &= \hat{K}\,\frac{\overline{K}+Q}{\hat{K}+Q} \\ Q &= \frac{\tilde{K}}{n}\cdot\frac{\hat{K}-\overline{K}}{\hat{K}-\tilde{K}} \\ \mu &= \bar{\mu} \end{aligned}\right\}. \tag{5}$$

For non-rigid media ($\overline{M}=0$), (5) reduces to the Wood (1930) equation,

$$\frac{1}{K} = \frac{n}{\tilde{K}} + \frac{(1-n)}{\hat{K}} \tag{6}$$

together with

$$\mu = 0 \tag{7}$$

Gassman also treated the anisotropic medium and developed expressions for the C_{ij} in terms of the $\overline{C}_{ij}$, $\tilde{K}$ and n.

In the imperfectly coupled system we have seen that two equations of motion are required, one for the frame and one for the pore-filler. The effective elasticity in this case will be affected by the relative displacement of the two constituents. Equation (6) is based on the fact that the volume displacement of the medium is the sum of the volume displacements of the constituents. This is not the case where the pore-filler is allowed to flow out of the pores. The Hooke's law equations (2) must now be replaced by:

$$\left.\begin{aligned} \bar{p}_i &= -\sum_{j=1}^{6} C_{ij}\cdot e_j - \bar{C}_i(\bar{e}_1 + \bar{e}_2 + \bar{e}_3) \\ \tilde{p} &= -\sum_{j=1}^{6} \tilde{C}_i\cdot e_i - \tilde{K}(\bar{e}_1 + \bar{e}_2 + \bar{e}_3) \end{aligned}\right\} \tag{8}$$

where $\bar{C}_i$ is the contribution of each constituent to the elasticity of the other.

Only in the completely decoupled system (Gassman's "open" system) does $\bar{C}_i = 0$. In this case, as may be seen from (8), the elasticities of the separate constitutents are unaffected by the presence of the other.

It should be noted here that in all systems the effective elasticity is a function of the elasticity of the frame. The evaluation of this quantity must precede the solution of the problem of the porous medium. Experimentally this may be done by direct measurement in vacuo if the pore-filler can be completely removed. Alternatively, a theoretical model may be devised to suit the medium and the elasticity calculated. Gassman (1950b) does this for a hexagonal frictionless packing of spheres.

The following expressions for velocity are obtained by solution of wave-equations similar to (3). Three systems are considered.

A. *Perfect Coupling*

A single wave is propagated, with velocity

$$c_i = \sqrt{\frac{\overline{C_i}}{\rho}} \tag{9}$$

where $C_i = C_i(\overline{C}_i, \tilde{K}, n)$, (evaluated by Gassman, 1950a), and ρ is given by equation (4).

For the isotropic medium equation (9) reduces to:

$$\left.\begin{aligned} c_1 &= \sqrt{\frac{\overline{M}}{\rho}} \\ c_2 &= \sqrt{\frac{\overline{\mu}}{\rho}} \end{aligned}\right\} \tag{10}$$

wherein the K and μ are given by equation (5).

In the case of zero frame-strength equations (10) become:

$$c = \sqrt{\frac{\overline{K}}{\rho}} \tag{11}$$

where K is given by equation (6).

Equations (9) and (10) were derived by Gassman (1950a) and applied to the problem of a water-filled sandstone. Equation (11) was used by Wood (1930)

and Chambré (1954) for non-rigid systems. Lester (1932) applied equation (11) to the problem of aerated surface layers of sand to explain the low velocity of seismic waves. It is doubtful if the model was suitable in this case, but it has been applied successfully to emulsions and suspensions.

B. *Zero Coupling*

Two waves are propagated, and these are called here the "air-wave" and the "frame-wave". The former should strictly be called the "pore-filler-wave," but since the system is only approached when the pore-filler is extremely light and air is the constituent commonly used, the term "air-wave" is adopted here.

The velocities are given by:—

$$\text{air-wave:} \qquad c = \sqrt{\frac{\overline{\tilde{K}}}{\overline{k\tilde{\rho}}}} \tag{12}$$

$$\text{frame-wave:} \quad c_i = \sqrt{\frac{\overline{C_i}}{\tilde{\rho}}} \tag{13}$$

In equation (12), which is the expression used by Ferrero and Sacerdoté (1951), k is the structure-factor referred to earlier in the paper. The expression allows for the evaluation of k through measurement of c in porous air-filled systems.

Equation (13) is taken from Gassman (1950a). As in equations (9) and (10), the elasticity of the frame is involved. Gassman (1950b) calculates the six elastic constants of a hexagonal packing of spheres and applies these to the problem of a sand formation held together by gravitational forces. The geological basis for this is the work of Graton and Fraser (1935) wherein it is shown that assemblages of equal-sized grains do tend to pack with transverse, and largely hexagonal, symmetry. It should be noted here that expression (13) allows for the evaluation of $\overline{C}_i$ if the c_i can be measured experimentally in an air-filled system.

C. *Imperfect Coupling*

The problem of the imperfectly coupled system is much more difficult.

Biot (1955) has treated the anisotropic system by writing equations of motion for the frame and the pore-filler and combining these with the stress-strain equations (8). While his expressions take into consideration the effects of relative displacement on the accelerating forces and the elasticity, they appear to disregard the effects referred to above as "Inertia" and "Texture." Thus, the density that appears in the equation of motion of the framework is that of the entire medium. This is greater than that effective if the displacements are not completely coupled and leads to lower frame-wave velocities. The density used in the equations of motion for the pore-filler is that of the pore-filler alone. This should be modified to allow for the contribution of the frame. It should also allow for the effect of texture by means of a structure-factor as in equation (12) above.

Zwikker and Kosten (1949) treated the case of plane harmonic waves in an isotropic porous medium. Consideration was made of all the complicating factors mentioned above and expressions were derived which appear to apply to a very wide range of media.

Two dilatational waves result and these are termed the "frame-wave" and the "air-wave" or the "frame-wave" and the "liquid-wave" depending upon the nature of the pore-filler. Both waves involve volume displacements in both constituents. The ratio of the displacement speeds serves as an indication of the roles played by the two constituents.

In the air-filled system, the wave which has the highest ratio of air-wave speed to frame-wave speed is termed the "air-wave." The other is termed the "frame-wave." The wave-velocities are found from the propagation constants of the waves.

If

$$\gamma = \alpha + \frac{j\omega}{c} \tag{14}$$

represents the propagation constant of a wave of frequency ω, velocity c, and damping coefficient α, γ_{frame} and γ_{air} and hence c_{frame} and c_{air} may be obtained by solution of the following equation:

$$\Gamma^4 - \Gamma^2\left[\frac{n\tilde{\rho}+S}{n\overline{M}} + \frac{n\tilde{\rho}+S}{n\tilde{K}} + \frac{\tilde{\rho}(1-n)+S}{\overline{M}\tilde{K}}\cdot\frac{(1-n)(\tilde{K}-P_0)}{n} + \frac{n\tilde{\rho}\tilde{\rho} + (\bar{\rho}+n\tilde{\rho})S}{n\overline{M}\tilde{K}}\right] = 0$$

where

$$\left.\begin{aligned} \Gamma &= \gamma/j\omega \\ S &= s/j\omega \\ s &= j\omega n\tilde{\rho}(k-1) + n^2\sigma \\ \sigma &= \frac{\operatorname{grad}\tilde{p}}{\tilde{v}} \text{ (where } \tilde{v} \text{ is volume displacement velocity)} \\ P_0 &= \text{equilibrium air-pressure} \end{aligned}\right\} \tag{15}$$

The quantity s is termed the "coupling coefficient." Multiplied by the relative displacement velocity, it provides an additional force term in the equations of motion. The first term of the coupling coefficient allows for the effects of texture and the partial contribution of one constituent to the inertia of the other. The second term provides the viscous force.

The quantity σ, is termed the "specific flow resistance." It may be related to the directional permeability, $\boldsymbol{K}$, through the equation

$$K = \frac{\eta \bar{v}}{\text{grad } \bar{p}} \tag{16}$$

The ratio of volume displacement speeds is:

$$\frac{\bar{v}}{\tilde{v}} = \frac{(1-n)(\tilde{K}-P_0)\Gamma^2 + S}{-n\tilde{K}\Gamma^2 + n\tilde{\rho} + S} = -\frac{nM\cdot\Gamma^2 + n\bar{\rho} + S}{n(1-n)\tilde{\rho} + S} \tag{17}$$

Equation (15) provides solutions for wave-velocities, attenuations and the dependence of wave-velocity on frequency (the dispersion). Equation (17) supplies a measure of the degree of coupling.

In the above equations, it has been assumed that $\tilde{K} \ll \hat{K}$, which is true in the case of air. Where water or other liquid is the pore-filler, $\tilde{K}$ must be replaced by nK, K being the quantity given by equation (6).

By this substitution and by putting $\overline{M} = 0$, Nolle (1953) found expressions for wave-velocities and attenuations which he applied to loosely packed water-filled sands. The value of the structure-factor was borrowed from Ferrero and Sacerdote (1951);

$$k = 4.3n \tag{18}$$

and the resistance constant σ was evaluated from the expression

$$\sigma = \frac{1}{0\cdot 12na}\sqrt{2\tilde{\rho}\eta\omega} \tag{19}$$

which was derived experimentally by Thurston and Martin (see Nolle, 1953) for packings of equal-sized spheres.

It should be noted here that expressions (10), (11), (12) and (13) are compatible with the solutions of the more general expression (15). For the perfectly coupled medium it is sufficient to put η infinitely high. For the case of weak coupling, ρ, $\tilde{K}$, and η must be made very small.

EXPERIMENTAL TECHNIQUE

The technique adopted by the author differs in one or two respects only from that described by O'Brien (1955) for work in the same laboratory. Only the differences will be discussed in any detail in this paper.

The apparatus is shown in the block diagram (Fig. 1) and in the photographs (Plate 1).

A pulse technique was used with a variable repetition rate of 25 to 250 c.p.s. and an output of up to 1,500 volts. Timing was performed by means of a variable acoustic delay-line. Piezo-electric transducers were used as source and receiver in both the medium and the timer. The source was a barium titanate cylinder 2 inches long by 1 inch in diameter with walls $\frac{1}{8}$ inch thick. Receivers were 1 inch diameter by $\frac{1}{4}$ inch thick discs, also barium titanate. Source transducers in the medium and the timer were arranged in parallel. The medium was placed in an 8-inch diameter cylindrical container and was loaded vertically by means of a brass plate and rod and a lever (Plates 1(b) and 1(c)). The source was inserted

centrally, and four receivers were placed in the same plane and on the outside of the container. Cylindrical symmetry was thus achieved. The vertical load could be varied from 6 kg. to 35 kg. Good coupling was obtained between source and medium and receivers and medium. At the same time, early events travelling in the walls were prevented. Late events through reflections and refractions caused some trouble and different containers were devised to reduce this. A thin plastic bag inserted in a large styrofoam block (Plate 1(c)) was found to be satisfactory in eliminating late events but provided rather weak signals. The lucite container

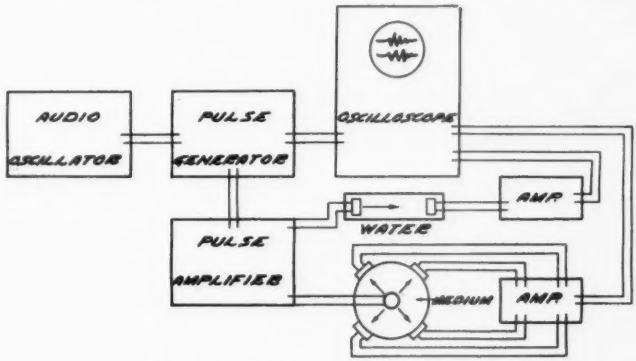

FIG. 1. Block diagram of apparatus.

(Plate 1(a)) provided good signals, and the late events did not prove too troublesome. The signals from the four receivers were added together, amplified and fed to the upper trace of a twin-beam oscilloscope. The signal from the timer was fed to the lower trace. The timer was calibrated against a 100 kc. signal from an oscillator which was triggered by the driving oscillator and damped to decay between pulses. The timing transducers were placed in a water tank and the distance between them was measured by a meter-stick. Times from 20 to 800 micro-seconds were measured to an accuracy of 1 percent.

Materials used as porous media consisted of glass beads 6 mm. and 0.6 mm. in diameter and graded quartz sands varying in size from 20–30 mesh to 40–50 mesh. Photomicrographs of these and a Pleistocene Beach Sand are shown in Plate 2. Pore-filling materials were air, water and glycerine.

Provision was made for shaking the specimens to ensure the most stable packing and for evacuating them before the insertion of liquid. Both these operations were found to be most important.

SOME RESULTS

A. The dry medium

In Plates 3(a) to 3(c) photographs are shown of the pulse received through dry 20–30 sand at increasing vertical loads. The lower trace shows the timing

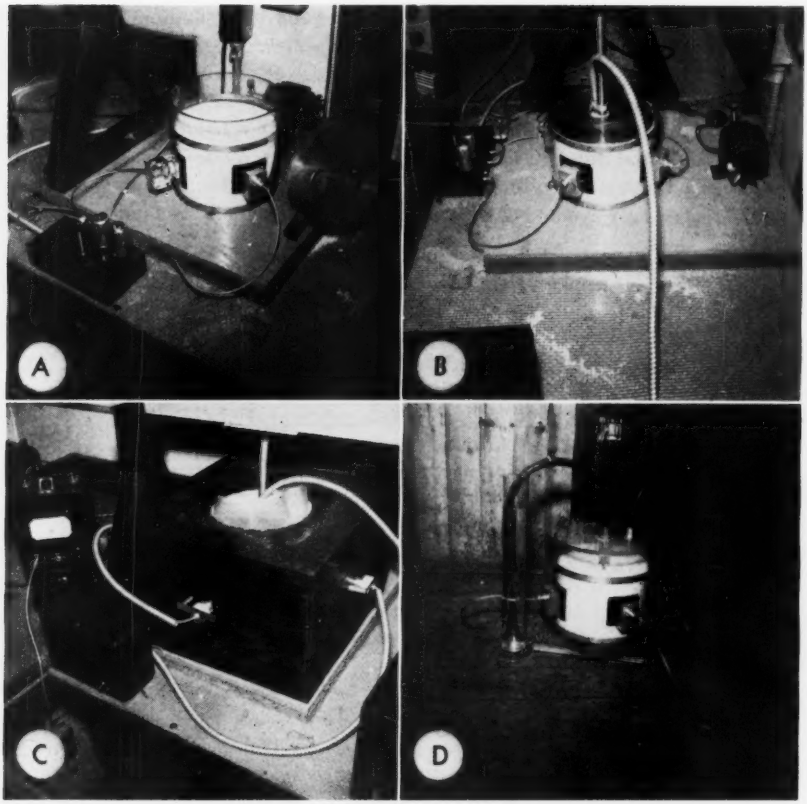

PLATE 1. The containers. (A) Lucite container, top removed, showing source and receiver transducers. (B) Lucite container, top on, showing loading rod, shaking mechanism. (C) Styrofoam container, top on, loading beam in place. (D) Lucite container under vacuum, water being introduced.

signal with a frequency of roughly 50 kc. The upper trace shows the two waves that are received through the dry medium. Both are of low frequency (about 5 kc.) and both increase in speed as the load is increased. The later wave increases more rapidly and in Plate 3(c) it has overtaken the earlier one.

Fig. 2 shows the experimental results from tests on 20–30 sand plotted as graphs of velocity against the one-sixth power of the load. Curve number 1 is interpreted as representing the air-wave, curve number 2 represents the dilatational frame-wave, and curve number 3 is thought to represent the shear frame-wave. Plotted on the same graph are curves calculated using the theories of Ferrero and Sacerdoté (1951), (equation (12)) and Gassman (1950a), (equation (13)). Curve number 4 shows the theoretical air-wave, curve number 5 shows the

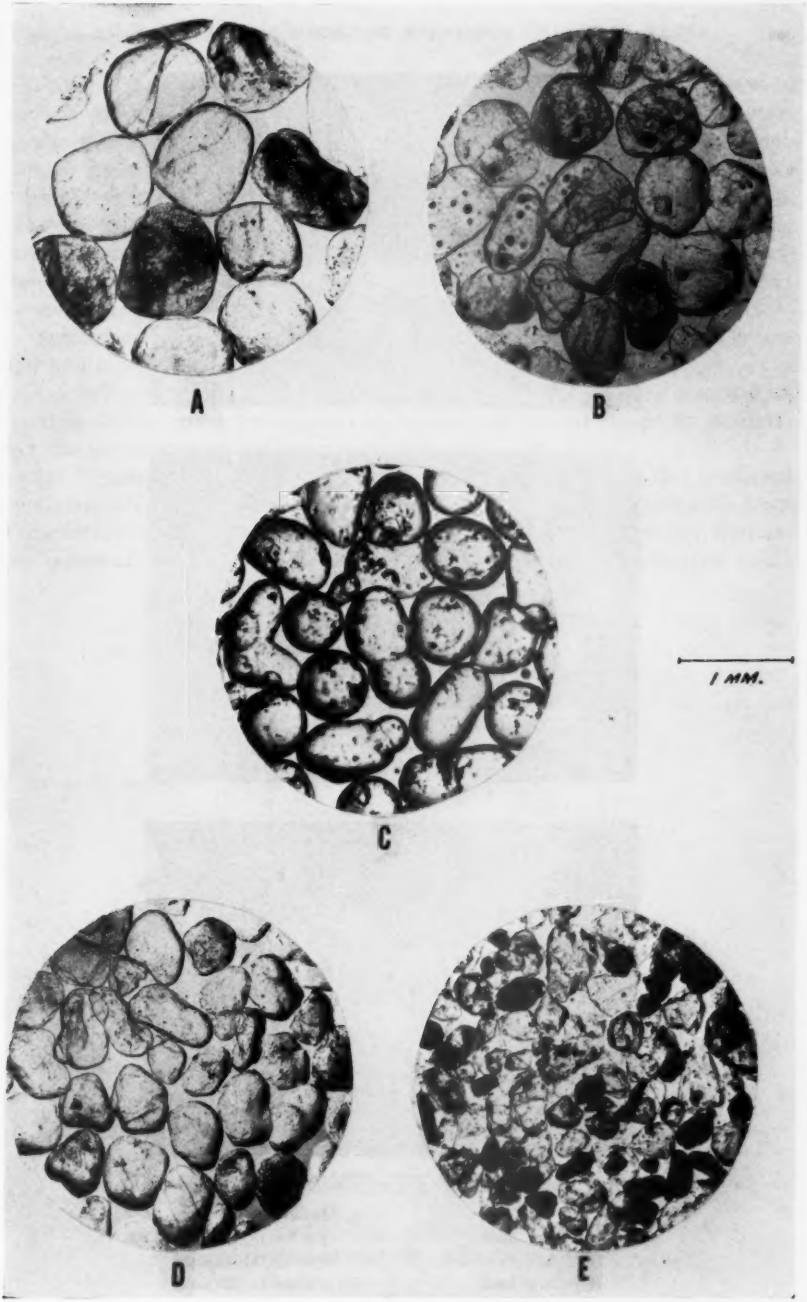

PLATE 2. Some of the media. (A) 20–30 quartz sand. (B) 30–40 quartz sand. (C) 30–35 (0.6 mm.) glass beads. (D) 40–50 quartz sand. (E) Pleistocene beach sand.

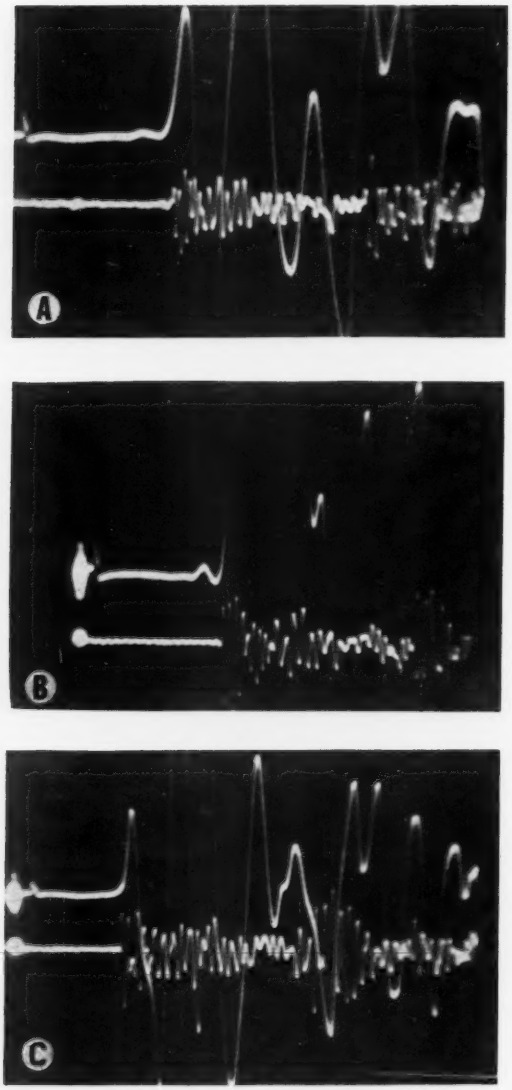

PLATE 3. The pulse through dry 20–30 sand. (Variation with load.)

	Oscilloscope Settings
(A) Small load	500 mv./1,500 μsec.
(B) Medium load	150 mv./1,500 μsec.
(C) Large load	1,500 mv./1,500 μsec.

dilatational frame-wave and curve number 6 shows the corresponding wave of vertical shear. It will be seen that the theoretical frame-wave curves show up as straight lines with this choice of absicssae. Curves numbers 7 and 8 are calculated from Zwikker and Kosten's (1949) equations (15), using Gassman's (1950b) value of the "specific stiffness" for horizontal propagation of dilatation. It is seen that only at very low frame-strengths do these curves differ appreciably in form from the simplified ones of Ferrero and Sacerdoté and Gassman. Velocities calculated by means of the Wood (1930) equation (11) are of the order of 15 to 20 metres per second.

Some remarks are now made regarding the interpretation of the above results and results on the other media.

(1) Velocity of the air-wave is higher than that predicted by the theory. This could be due to incorrect evaluation of the structure constant aided by inaccuracies due to the weak signal corresponding to this wave.

(2) Velocity of the frame-wave is roughly $2\frac{1}{2}$ times as high as that predicted by Gassman (1950b) but shows approximately the correct increase with load. The elastic constants of the frame appear to be about 7 times those of a frictionless hexagonal packing of spheres. That friction exists in the experimental media

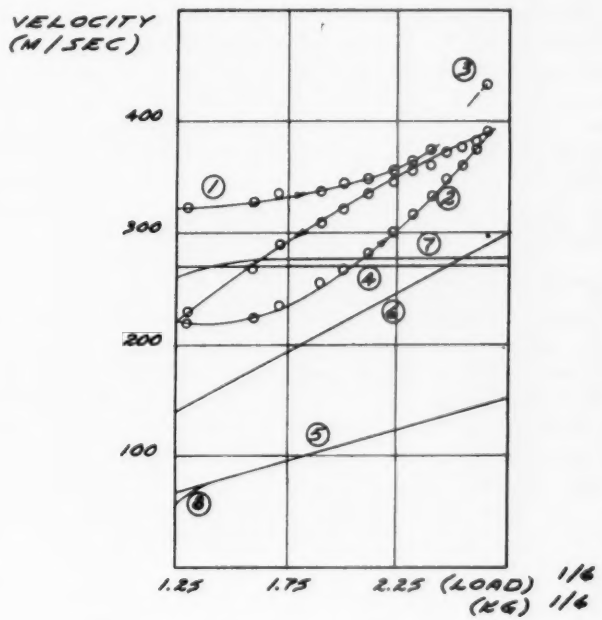

FIG. 2. Velocity variations with load in dry 20–30 sand.

is shown by the "hysteresis" effect or lag of velocity changes behind pressure changes in Figure 2.

(3) A wave corresponding to Gassman's (1950b) wave of vertical shear appears at very large loads in the sand specimens and is present at all loads in the glass beads. For transmission of this wave good frictional coupling between medium and transducers and between grains of the medium are apparently required. The wave is roughly 1.5 times as fast as the dilatational wave, whereas Gassman predicts that it is twice as fast.

(4) Attenuation of the air- and frame-waves is seen to be high at high frequencies since the waves contain only the low frequency component of the transmitted pulse. Calculation by means of equations (15) provides attenuation of 1.2×10^{-4} at 50 kc. and .091 at 5 kc. for the air-wave in the 10 cms. between source and receiver. The calculated attenuation of the frame-wave reaches a maximum of 0.9 at 50 kc. and at low loads, and does not decrease much on lowering the frequency. Thus good agreement is seen for the air-wave but poor agreement for the frame-wave. Better agreement would be achieved if the value of flow resistance were increased.

(5) The degree of coupling of the air- and frame-waves may be examined by means of equation (17). The ratio of volume displacement velocities of air and solid is found to be of the order of 10:1 for the frame-wave and 500:1 for the air-wave at large loads decreasing to 200:1 at small loads. The decrease in the ratio, or the improvement of coupling of the air-wave at decreasing loads, shows the increasing contribution of the solid to the inertia of the system. It accounts for the decrease in the calculated air-wave speeds at very small loads.

(6) The absence of a wave corresponding to the coupled wave of Wood (1930) and Chambré (1954) is significant. The very low velocity waves observed by Lester (1932) were probably frame-waves through surface layers of very low frame-strengths.

B. The liquid-filled medium

Plate 4 shows the pulse received through water-saturated 0.6 mm. glass beads. In Plate 4(a) two waves are seen; an earlier one of high frequency and a later one, marked by the start of the timing signal, of low frequency. In Plates 4(b) and 4(c) the waves are viewed separately at increased oscilloscope sweep-speeds. Estimates of frequency may be made by reference to the timing signal which is roughly 50 kc. It will be shown that the earlier wave is the water-wave and that the later is the frame-wave.

Water-waves through three different sands are shown in Plate 5. All show the same high frequency and all are of roughly the same speed.

Plates 6(a) and 6(b) show water- and frame-waves through 20–30 sand at two different loads. The speed of the water-wave is seen to remain the same while that of the frame-wave, which is marked by the start of the timing signal, increases rapidly with increasing load.

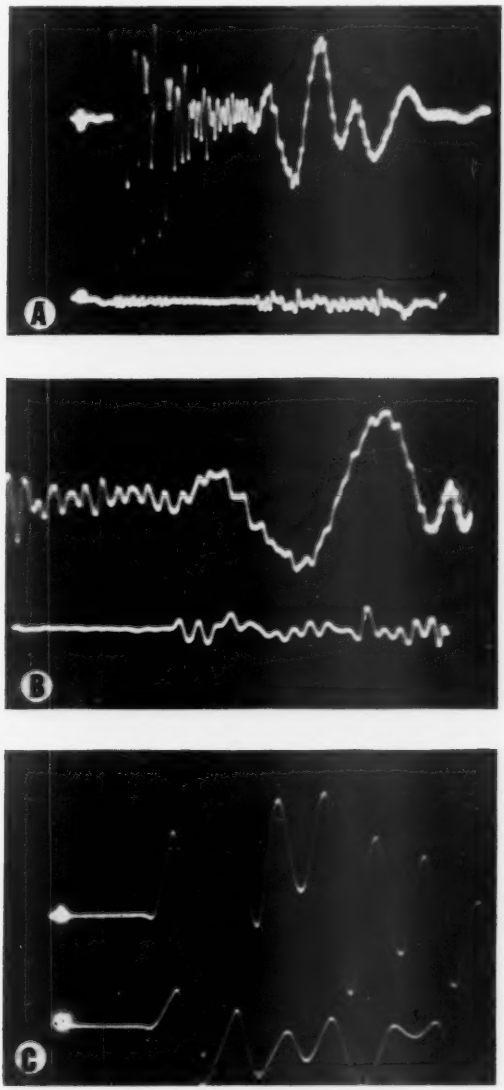

PLATE 4. The pulse through water-saturated 0.6 mm. glass beads. (Two waves)

	Oscilloscope Settings
(A) Both events	1,500 mv./1,500 μsec.
(B) Late event	1,500 mv./500 μsec.
(C) Early event	1,500 mv./150 μsec.

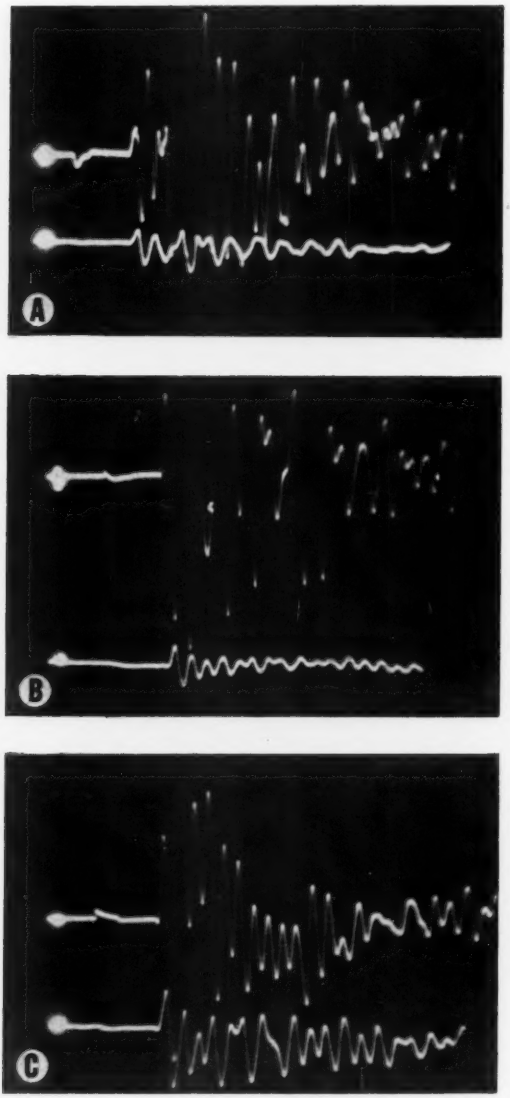

PLATE 5. The water-wave through three water-saturated sands.

	Oscilloscope Settings
(A) 20–30 sand	1,500 mv./500 μsec.
(B) 30–40 sand	1,500 mv./500 μsec.
(C) 40–50 sand	1,500 mv./500 μsec.

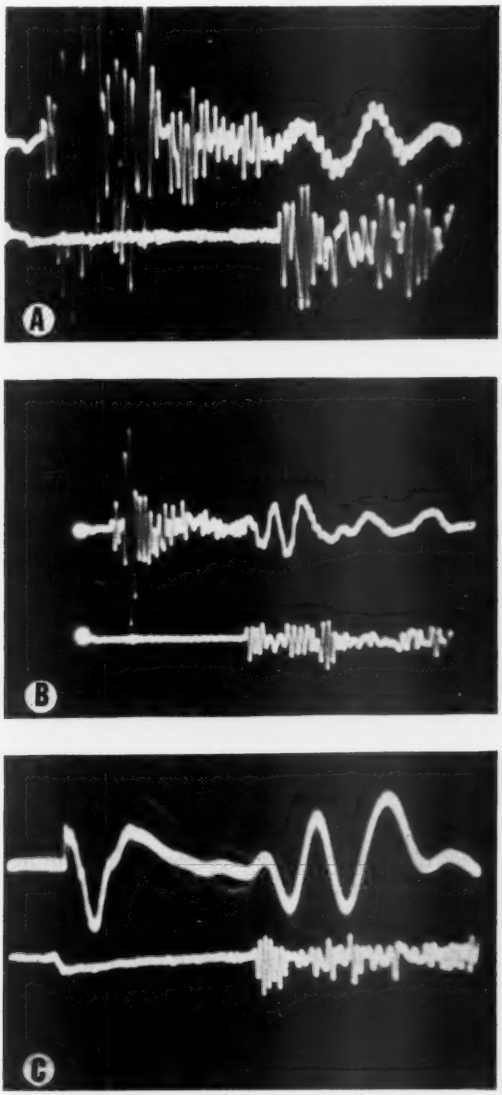

PLATE 6. The pulse through liquid-saturated 20–30 sand.

	Oscilloscope Settings
(A) Water-saturated. Small load.	1,500 mv./1,500 μsec.
(B) Water-saturated. Large load.	5,000 mv./1,500 μsec.
(C) Glycerine-saturated. Medium load.	500 mv./1,500 μsec.

The pulse shown in Plate 6(c) has travelled through glycerine-filled 20–30 sand. Again two waves are observed. This time, however, the earlier or glycerine-wave is not of the same high frequency. The very sharp first-break of the wave may be explained by dispersion.

The following comments are made regarding the interpretation of these results:

(1) The speed of the liquid-waves may be compared with speeds calculated by the Gassman (1950a) equation (9). At the low frame-strengths prevailing in the experiments this equation reduces to the Wood (1930) equation (11). Theoretical and observed velocities for four media are listed below.

	Theoretical m./sec.	*Observed* m./sec.
Water-filled:		
20–30 sand	1,570	1,650 ± 30
40–50 sand	1,550	1,670 ± 30
0.6 mm. beads	1,560	1,690 ± 30
Glycerine-filled:		
20–30 sand	2,190	1,960 ± 40

The results for the water-filled media are similar to those of Nolle (1953). The theoretical values are low because of assuming perfect coupling and hence a too high effective inertia. The theoretical value for the glycerine-wave is believed to be in error due to inaccurate assumed values for dynamic bulk modulus and viscosity.

Liquid-wave speeds are now re-calculated using the Zwikker and Kosten (1949) equations (15).

	Theoretical m./sec.	*Observed* m./sec.
Water-filled		
20–30 sand	1,670	1,650 ± 30
40–50 sand	1,660	1,670 ± 30
0.6 mm. beads	1,770	1,690 ± 30
Glycerine-filled:		
20–30 sand	2,190	1,960 ± 40

The agreement for the water-waves is now good. The error in the case of the 0.6 mm. beads is less than 5 percent. This is small considering the probable errors in the measured porosity, the assumed elasticity and the borrowed value for the structure-factor.

(2) In Fig. 3 the observed velocities of the frame-waves in water- and glycerine-filled 20–30 sand are compared with those calculated by means of Zwikker and Kosten's equations (15). Curves number 1 show the observed values on increasing and decreasing loads. Curves number 2 show the theoretical values assuming a specific stiffness equal to Gassman's (1950b) effective elastic constant for horizontal propagation of dilatational waves in a hexagonal packing of spheres. Curves number 3 show the values obtained by taking a stiffness constant from the experimental results on the dry medium using equation (13). Remarkably good agreement is seen between curves numbers 1 and 3.

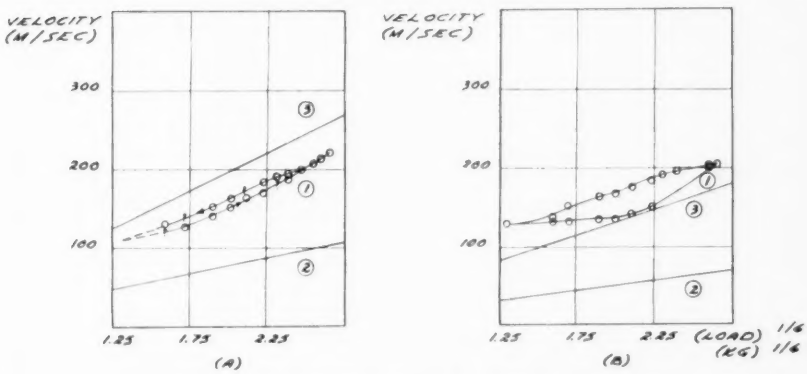

FIG. 3. Velocity variations with load in liquid-filled 20–30 sand.
(A) Water-filled sand. (B) Glycerine-filled sand.

(3) The absence of high frequency in the frame-waves in the liquid-filled media is due to attenuation. The calculated attenuation at 50 kc. and at high loads is 0.70 in water-filled 20–30 sand and .0063 in glycerine-filled 20–30 sand in the 10 cms. between source and receiver. The attenuation of the water-wave at 50 kc. is only 0.97 while that of the glycerine-wave is 0.75. As in the case of the dry media, most of these values seem to be high though qualitative agreement is seen with the observed results. Better agreement would be obtained if the theoretical flow resistance was increased.

(4) Coupling of the waves in the liquid-filled media is generally good. The ratios of volume displacement velocities of liquid- to frame-waves, as calculated from equation (17), are listed below:

Water-filled 20–30 sand, (maximum load);	
frame-wave	1.7
water-wave	1.9
Glycerine-filled 20–30 sand, (maximum load);	
frame-wave	1.2
glycerine-wave	1.3

Coupling improves with a decrease in frequency and an increase in flow re-resistance. The coupling of the liquid-waves improves as the frame-strength is decreased.

EXPERIMENTS WITH A BEACH SAND

A specimen of unconsolidated (Pleistocene) beach sand was collected by the author. A photomicrograph is shown in Fig. 2. The composition of the sand is over 90 percent quartz, the remainder largely fine-grained rock fragments. A rough size analysis was carried out and is shown in Fig. 4.

The specimen was tested both dry and saturated with water. The measured wave-velocities are shown in Fig. 5. An attempt is made below to infer some

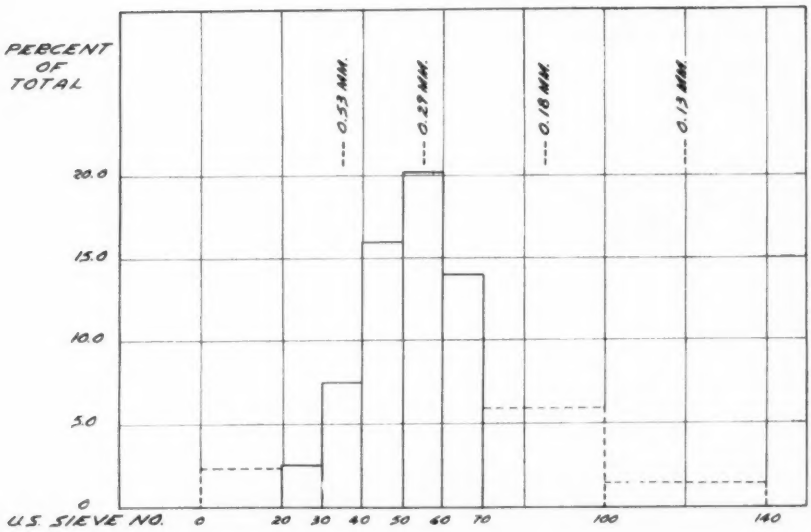

FIG. 4. Size analysis of beach sand.

properties of the specimen by comparison of its behaviour with those of the experimental models.

The frame-wave curves for both the dry and the water-filled media show velocities slightly lower than those of the other sand specimens. By referring to equations (9) and (15) we find that the elastic constants of the frame must be weak, the density high, or the porosity low. Since the elasticity and density are approximately those of quartz we can conclude that the porosity is lower than in the other sand specimens.

The air-wave speed in the beach sand is higher than in any other medium. The speed of the air-wave as calculated by the Zwikker and Kosten (1949) equations (15) or by the Ferrero and Sacerdoté (1951) equations (12) and (18) is affected by the framework through the porosity only. It was found in experiments on the graded sands that porosity increased as grain-size decreased and that this accounted for the observed decrease in air-wave speed in the finer grained specimens. The high air-wave speed in the beach sand therefore points to a low porosity. Though the variation in speed with load may be due to a decrease in the influence of flow-resistance at large loads, much greater values of flow resistance would be required than those calculated by means of Nolle's (1953) equation (19). No inference should therefore be made regarding flow-resistance from the results of the tests on the dry medium alone.

Low porosity is consistent with the measured value of 0.37. This is equal to the value found for 20–30 sand, the coarsest specimen used in the experiments.

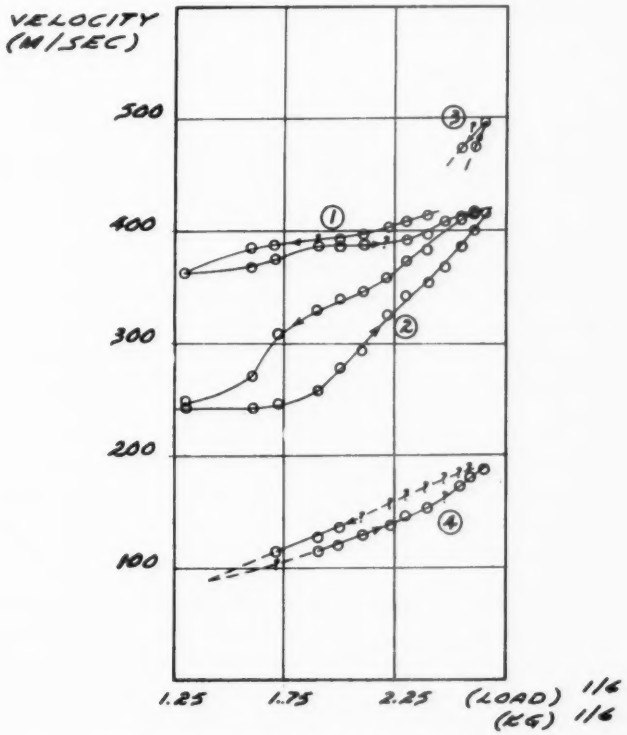

FIG. 5. Velocity variations with load in beach sand. Curves (1) to (3), specimen dry. Curve (4), specimen water-saturated.

The water-wave speed in the beach sand was found to be $1,530 \pm 30$ metres/sec. This is significantly lower than in the other media. This may be explained by an increase in the viscosity component of the coupling coefficient, s, of equations (15). Thus the flow-resistance of the medium is high and the permeability low.

Low permeability means that grain-size is small, since there is no cementation. Low porosity is consistent with the fact that the specimen is imperfectly sorted in contrast with the sands used as the experimental models.

The limiting value for the water-wave speed at high values of flow-resistance is that given by the Wood (1930) equation (11). For sand with a porosity of 0.37, the limiting velocity is 1,560 metres/sec. This agrees with the measured water-wave speed within the experimental error.

It is not possible to compare the dynamic flow-resistance, σ, required for this limiting case with the known properties of the specimen.

The steady-flow permeability of the specimen may be estimated by means of Krumbein's (1942) empirical formula. We obtain:

$$K = 40 \text{ darcys}$$
$$= 4 \times 10^{-7} \text{ cms.}^2$$

The dynamic permeability required to justify using the Wood equation (11) is:

$$K \ll 2 \times 10^{-7} \text{ cms}^2.$$

(using equation (16)).

Comparison of these values would require a knowledge of the relation between steady-flow and dynamic flow-resistance in granular aggregates.

It is probable that at the low permeabilities prevailing in sand formations (5 darcys is the highest permeability the author has seen reported), the Wood formula will always apply for the calculation of the water-wave speed.

SUMMARY AND CONCLUSIONS

The research described in this paper touched on a rather large number of problems. A few of these have been solved. To others, tentative answers have been given. Some have been left unanswered. The following list is considered to be of value in summarizing the scope of the research and indicating what progress has been made.

(1) An experimental technique has been developed by which the velocity of elastic waves in unconsoliadted media may be measured with fair accuracy. The technique also allows measurement of frequency and amplitude. Events may be observed which arrive at times as large as ten times that of the first arrival. Media may be tested dry or saturated with a liquid.

(2) The two waves of volume expansion which involve coupled movements of both constituents of the medium have been viewed, photographed and analyzed. Though these waves have been predicted by several writers, no mention of their having been observed experimentally can be found in the literature.

(3) Simple theories advanced by Wood (1930), Gassman (1950a) and Ferrero and Sacerdoté (1951) have been reviewed and compared with the more general theories of Zwikker and Kosten (1949) and Biot (1955). The physical meaning of the simple systems has been noted.

(4) Observed values of velocity have been compared with those predicted by the general and the simple theories. The theory of Zwikker and Kosten is shown to provide fair agreement in nearly all cases. The simple theory of Ferroro and Sacerdoté provides an approximation for the air-wave in the dry medium with strong frame. The systems of Gassman are shown to correspond to perfectly decoupled and perfectly coupled media. The "open" system provides a frame-wave whose behaviour conforms with experiments in the dry media. The"closed" system provides a liquid-wave whose speed, at the low frame-strengths prevailing, is the same as that calculated from the simple Wood theory. The speed is less than

that obtained experimentally but approaches the observed value as coupling is improved.

(5) Frame-wave speeds are shown to vary roughly as the one-sixth power of the load, other factors remaining constant. The frame-strength therefore varies as the one-third power of the load. This result is in agreement with the theory developed by Gassman (1950b) and with the experimental work of Iida (1939). The variation of velocity with load is the same as that observed by Faust (1953) in sedimentary formations where the lithology does not vary.

(6) Elastic constants derived from the observed frame-wave velocities are higher than those calculated by Gassman (1950b) for a hexagonal packing of spheres. They are also higher than those that might be expected for un-geometrical packings. This may be due to friction between grains or to imperfect sphericity and roundness. The elastic constant controlling the horizontal propagation of vertical shear appears to be higher than that for the dilatational wave by an amount only slightly less than that predicted by Gassman. This result is unusual and may be of significance in interpreting field seismic observations.

(7) Attenuation of the observed waves was shown to be due primarily to viscous damping and to agree in order of magnitude with that predicted by the theory of Zwikker and Kosten. Scattering appears to provide attenuation only in the medium of largest grain size (6 mm.) and at the highest frequencies (roughly 50 kc.) In the other media it is not evident but it may be masked by the greater effect of viscous damping. These observations are in agreement with those of Nolle (1953).

(8) Dispersion is observed in one medium only (glycerine-filled sand), and this is predicted by the theory of Zwikker and Kosten.

(9) The degree of coupling of the waves in the experimental media has been studied. The waves in the dry media are shown to be loosely coupled while those in the liquid-filled media are strongly coupled. The factors affecting coupling and the effects of coupling on the speed and attenuation have been noted.

(10) Tests have been made on a specimen of beach sand. The results have been compared with those obtained with the simpler media and some information regarding the specimen has been inferred. In particular, the specimen was shown to have low porosity and low permeability. This is in agreement with fact. It seems probable that a quantitative interpretation would eventually be possible using methods similar to those adopted in this research.

(11) The author sees no reason why the mechanisms found valid for the unconsolidated media tested should not apply also to consolidated media. Experiments on these media are believed to be currently under way in several laboratories. Difficulty is foreseen due to the fact that at the higher frame-strengths, the frame-wave will be the first arrival and may obliterate the air- and liquid-waves. Frequency differences may assist in resolving the waves. It is hoped that the air- and liquid-wave velocities will eventually be of value in predicting porosity and permeability of sedimentary formations.

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GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 715-723, 9 FIGS.

SEISMIC WAVES FROM A HORIZONTAL FORCE*

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ABSTRACT

As part of a program of fundamental research on seismic waves, a generator was built for applying a transient horizontal force at the surface of the ground and the resulting seismic waves were observed in some detail. The force is applied when a mass swinging through an arc strikes a target anchored to the earth. Surface geophones along a line in the direction of the force register vertically polarized shear waves refracted back up to the surface, whereas geophones on a line perpendicular to the force register horizontally polarized shear waves. The speeds of the two types of shear waves are often different, indicating anisotropy. Geophones buried below the target show a down-going shear wave. Variation of amplitude with angle, and other features, are in qualitative agreement with the results given by Rayleigh and others for the waves due to a force at a point in an infinite solid. Love waves and other surface waves were observed, which of course would not be expected from an nterior force.

INTRODUCTION

Any theoretical treatment of wave propagation in a particular section of the earth requires a knowledge of its elastic constants and density. If the density is known, the elastic constants can be computed from measured speeds of shear and compressional waves. If the material is not isotropic, speeds of compressional waves in different directions must be known and speeds of shear waves in different directions and with different polarizations must be known. A discussion in Lord Rayleigh's *Theory of Sound* indicates that the application of a localized force in a solid material generates a strong shear wave. It was felt that a means of exerting a localized force at the surface of the ground would generate shear waves in this manner, and that detection of these waves at different distances along the surface would give shear speeds in shallow reflecting layers.

DESCRIPTION OF THE SHEAR SOURCE

A frame similar to a play-ground swing was built, with a four-cable suspension for a cylindrical mass, as shown in Fig. 1. Masses of 105, 290, and 515 pounds were used, swinging from heights up to 6 feet. At the bottom of the arc, the horizontally-traveling mass struck a plate at the junction of an X-shaped target of channel-iron which was anchored by means of about 12 stakes driven into the ground or cemented in auger holes.

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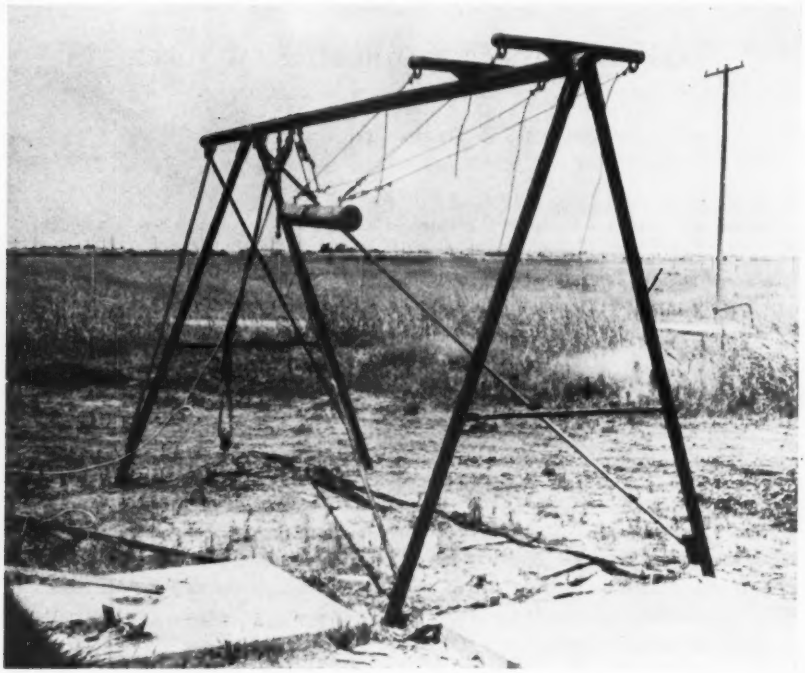


FIG. 1. Pendulum shear generator—Anchored metal target is not shown.

TYPES OF WAVES OBSERVED

This source was set up at several locations favorable for refraction of elastic waves. The Akin Farm, Kaufman County, Texas, is typical of locations having an abrupt increase in speed at a shallow depth as shown in Fig. 2. The velocity information was obtained by measuring vertical compressional and water-pulse signals in a borehole. The SH shear speed was computed from the water-pulse speed assuming that formation density was 1.5 times that of the borehole fluid. (White et al. 1953). A gradual increase in shear speed to a depth of 60 feet is indicated, with an abrupt increase at that depth. Paths for two critically refracted waves which might be expected in this situation are shown in Fig. 3. Along a radial profile perpendicular to the force, the refracted event is a horizontally-traveling shear wave with horizontal particle motion. The predominance of this mode is responsible for the term SH plane as indicated in the figure. Along a profile in alignment with the force, the refraction is a horizontally-travelling shear wave with vertical particle motion, hence SV plane. Refracted energy reaching the free surface will be reflected downward at the proper angle to be refracted to the

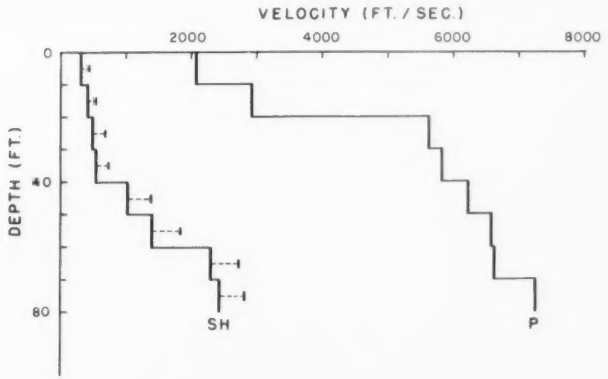


FIG. 2. Velocity logs at Akin farm.

surface again, so one should expect a train of multiple refractions. One might also expect that multiple reflections in the shallow layer would give rise to some form of low-frequency surface wave.

Signals from detectors along a line perpendicular to the force are shown in Fig. 4. As expected, the motion is essentially horizontal, the radial and vertical geophone signals being quite small compared with the transverse geophone signals. Note that the SH refraction is substantially the first energy on the record, followed by multiple refractions. A weak compressional signal can be seen on the vertical geophone. A time-distance plot in Fig. 5 shows the increase in refractor speed from 2,800 ft/sec to 3,200 ft/sec. The spacing between multiple refractions is about 0.17 sec, the round-trip time from the surface to the top of the refractor.

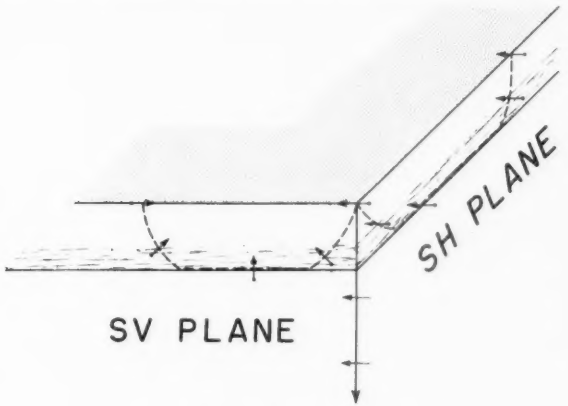


FIG. 3. Refraction paths for shear waves.

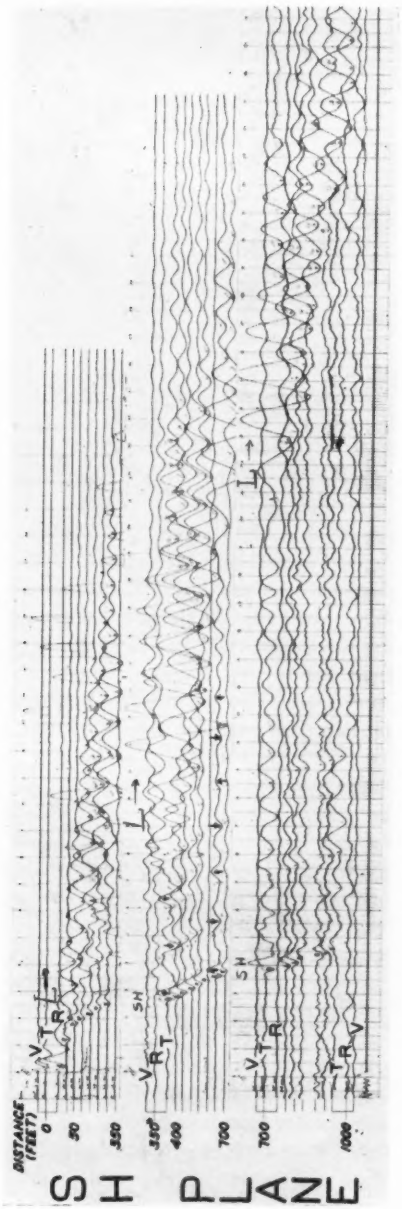


FIG. 4. Waves observed along line perpendicular to force (SH profile).

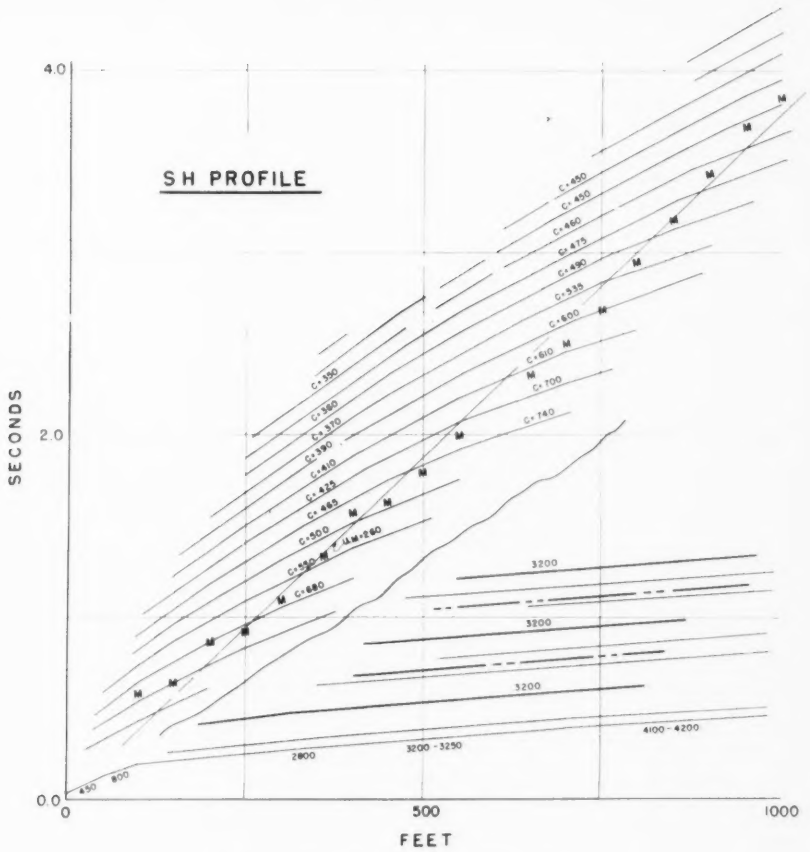


FIG. 5. Time-distance plot for SH profile.

These two results indicate that the SH speeds shown in Fig. 2, obtained from water-pulse speeds, are too low by about 20 percent. The well-defined low-frequency train marked *L* in Fig. 4 represents Love waves which arise from constructive interference of multiply reflected energy in the shallow layer. "*M*" on the time-distance plot, Fig. 5, indicates the cycle of this Love wave which has the maximum amplitude. Its observed periods varied from 0.17 sec. for early cycles to 0.09 sec. for late cycles. Phase velocities were obtained from slopes on the time-distance plot for the various cycles. Group velocities were obtained by dividing the arrival time of a given cycle into the source-detector distance for that trace. Fig. 6 shows group and phase velocities determined by these pro-

cedures plotted against wavelength. Note that good agreement is obtained between the measured group velocities, and the group velocity curve derived from the phase velocity curve.

Signals received along a profile in alignment with the force are shown in Fig. 7. The SV wave is clearly evident on radially sensitive geophones, although the onset is perhaps not as sharp as that for the SH profile. The time-distance plot shown in Fig. 8 shows the refractor speed to be 2,400 ft/sec, substantially less than

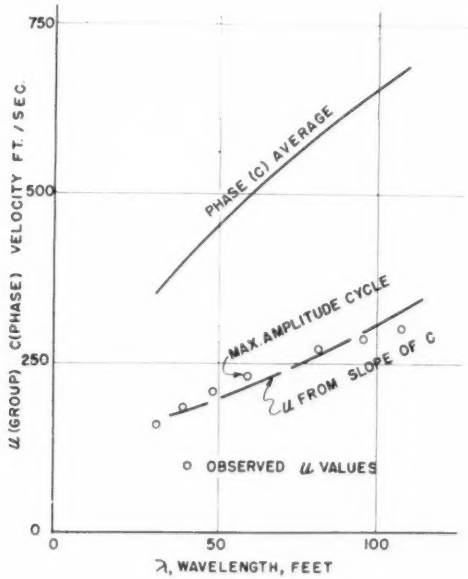


FIG. 6. Dispersion curve for Love waves observed on SH profile.

that for SH waves. Hence the refractor must not be completely isotropic. Succeeding cycles having the refractor velocity show the presence of multiple refractions, but it is not possible to pick out the individual pulses well enough to check the surface-to-refractor time. Fig. 3 shows how an SV wave starting downward with earth displacement in the direction of the impact force has its path bent in such a way that when the wave reaches the surface, the displacement is opposite to that of the force. This reversal was observed; the first motion of the SV events in Fig. 7 being opposite to that of the source. A surface wave observed in this direction has been marked "*D*" in Fig. 7. During its passage, particles follow elliptical trajectories in a vertical plane, but the motion is direct instead of retrograde, as would be the case for a Rayleigh wave. Group and phase velocities are about twice as large as those for the Love wave. The maximum cycle is

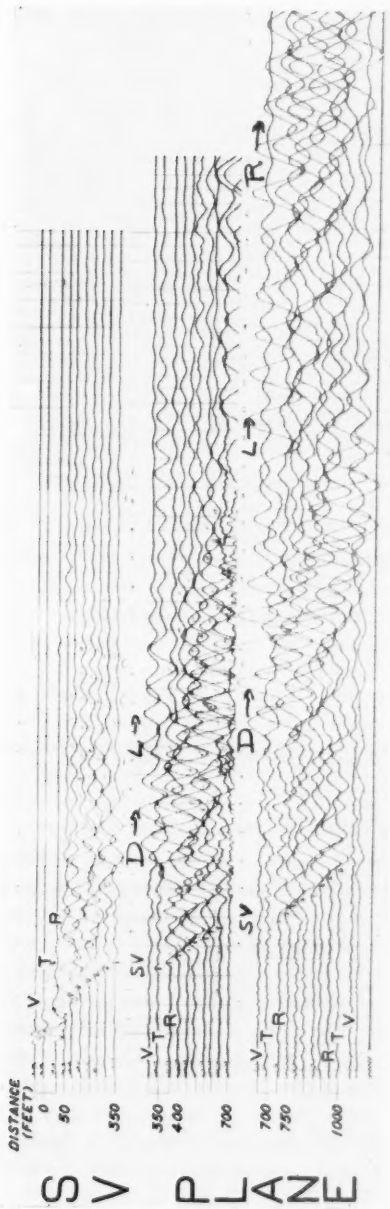
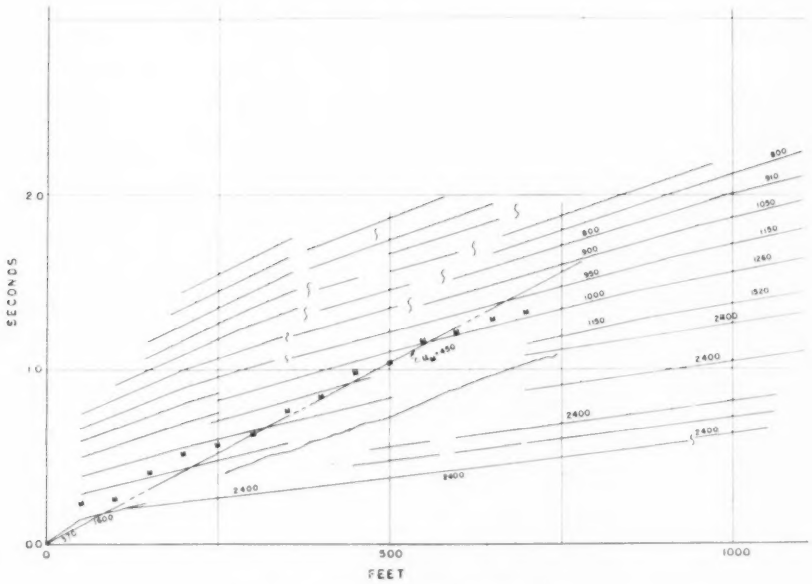


FIG. 7. Waves observed along line parallel to force (SV profile).


SECONDS
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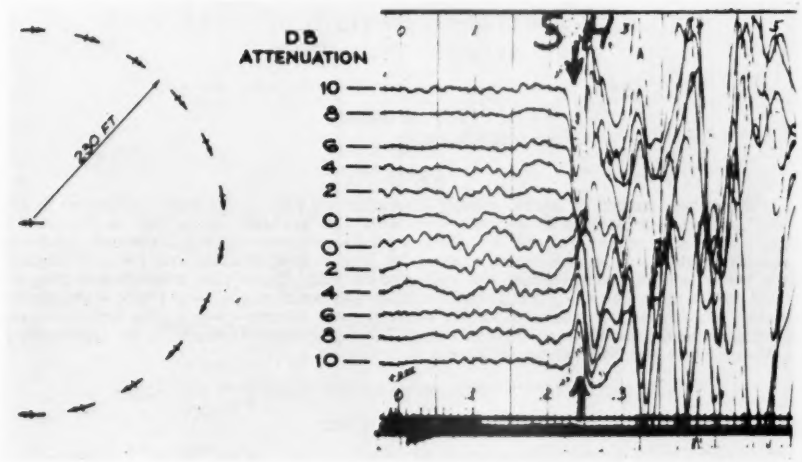

FIG. 9. SH arrivals observed on circular spread.

MEASUREMENTS BELOW SOURCE

In several instances, geophones have been clamped in boreholes below the shear source and the signal observed at several depths. At depths below about 100 ft, shear waves with substantially horizontal particle motion were observed and logs of shear speed were obtained. At closer distances, the motion was more complex and the shear component could not be separated.

CONCLUSIONS

The source described generates shear waves accompanied by very little compressional energy. Shear speeds for shallow refractors are obtained, and at several locations a significant amount of anisotropy is found. The SV refraction corresponds to shear refractions obtained from dynamite explosions (Dobrin et al. 1951–1954). This source also provides a means of obtaining a log of shear speed versus depth if used in conjunction with detectors lowered into a borehole. The Love waves observed are adequately explained on the basis of the layering present, but the "*D*" and "*R*" wavetrains (Fig. 7) exhibit some properties which are not explained by present theories of Rayleigh-wave propagation in layered media. Qualitatively the polarization and amplitudes of the refracted shear waves observed can be predicted from the analysis of a point force given by Rayleigh.

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GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 724–738, 17 FIGS.

THE LONG INTERVAL METHOD OF MEASURING SEISMIC VELOCITY*

F. P. KOKESH†

ABSTRACT

The reverse method of seismic velocity determination, wherein the shot is detonated in the bore hole, has been extended to operate in deep wells. This has been accomplished by the use of a long interval arrangement of a multi-shot selective firing sound source gun and one or more geophones separated vertically by a cable several hundred feet long. A series of a relatively few such intervals can "strap" a bore hole travel-time-wise with good accuracy. Travel time measurements over the cased portion of the hole can generally be accomplished by means of geophones placed at or near the surface. Velocity surveys conducted in this manner become a routine well logging service, in conjunction with other services such as electrical logs. The paper describes in a general way the necessary field equipment, and field examples of surveys are presented.

INTRODUCTION

A paper was presented about four years ago describing the so-called reverse method (Kokesh, 1952) of making seismic velocity surveys in bore holes, wherein an energy source in the form of a perforator gun is placed in the hole and the energy is detected by means of geophones at the surface (Fig. 1). The method has proved quite successful for shallow depths and numerous velocity surveys have been made in this way, mainly in core holes (Henderson and Brewer, 1953). Although successful surveys have been made under ideal conditions to depths exceeding 4,000 feet, the method was not found generally applicable in deep holes. Its use has been limited chiefly by the problems involved in placing large charges in deep holes, the nature of the energy propagated at depth, attenuation of energy in the weathered layer, and wind and other surface noise interference which may prevent using adequate sensitivity for recording.

There has, however, continued to be an interest in methods of obtaining accurate time-depth data in deep wells wherein operations are confined as much as possible to the bore hole. The long interval approach described in this paper is such a method.

GENERAL DESCRIPTION OF METHOD

In the long interval method, overall travel time is obtained by the summation of accurately measured travel times across successive intervals throughout the length of the open bore hole. Referring to Fig. 2, a suitable sound source, such as a conventional perforator gun, is lowered into the hole at the end of a logging cable. Geophones are located on the cable several hundred feet vertically above the sound source. Typical combinations of intervals from the gun are 400 feet

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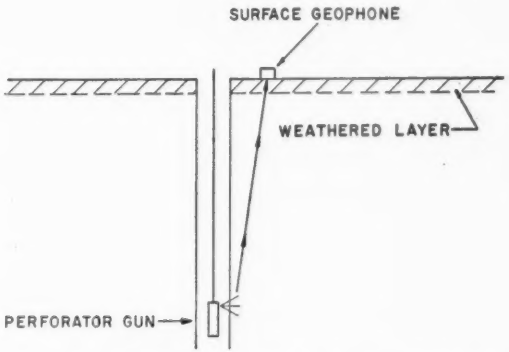

FIG. 1. The reverse method of measuring seismic velocity in bore holes.

and 800 feet respectively for the lower and upper geophones. This gives two simultaneous 400-foot interval measurements. The gun is a surface-controlled selective firing device, allowing as many as 48 shots per trip into the hole. The well geophones are connected through cable conductors to suitable recording equipment at the surface.

Total travel time over the entire open hole is obtained, as mentioned above, by simple addition of interval travel times as measured on the individual shots. In practice, the assembly is moved 400 feet at a time between shots so as to overlap, and thus double check, the interval measurements as shown in Fig. 3. Twenty-five shots will cover 10,000 feet of open hole, and since a shot may be made as quickly as one every three minutes, the survey can be made quite rapidly.

Measurements cannot be made in this manner in casing, since steel casing

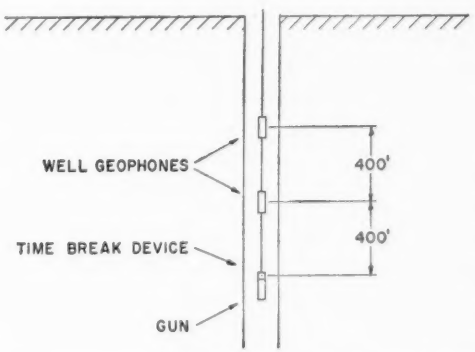

FIG. 2. The long interval method of measuring seismic velocity in deep bore holes.

usually has a higher velocity than the formations. The problem of surface and datum ties across the casing, using the reverse method, i.e., recording on geophones set at or near the surface from shots made just below the casing, is discussed in detail in a separate section below. As will be shown, datum ties across as much as 4,000 feet of casing can be obtained under suitable conditions. Where surface or protective casing is to be set to a greater depth, or in the event of adverse conditions at lesser depths, a datum tie can be obtained in the conventional manner, i.e., recording a surface shot on the well geophones set below casing. The preferred procedure, however, is to make a long interval survey before that casing is set.

A few remarks should be made about the equipment at this point before discussing field examples. Since energy can hardly be prevented from being trans-

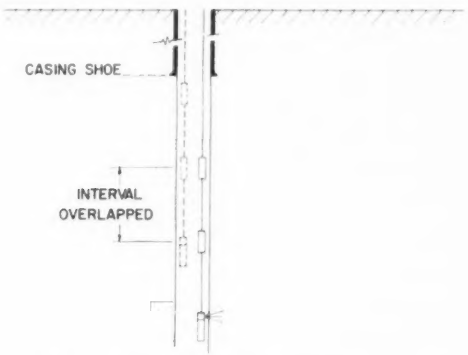

FIG. 3. The long interval method showing down-hole interval overlap.

mitted along the cable from the gun to the geophone, it is necessary to insure that the formation energy arrives ahead of the cable energy. A special low velocity cable has, therefore, been designed, which has a velocity of less than 6,500 feet per second, and yet has adequate strength and ruggedness to operate in deep wells.

Fig. 4 shows a photograph of a 24-shot perforator gun used as a sound source. A time break device or a geophone at the upper end of the gun responds to the mechanical shock generated at the instant of shooting and thus provides a time break for recording at the surface.

Concern has been expressed by some over the possibility of damage to the bore hole wall by shooting a gun in open hole. Such concern seems unnecessary, as thousands of shots have been made in open holes at all depths and in all kinds of formations without any evidence of damage to the bore hole.

Fig. 5 shows a photograph of one of the down-hole geophones and its mount-

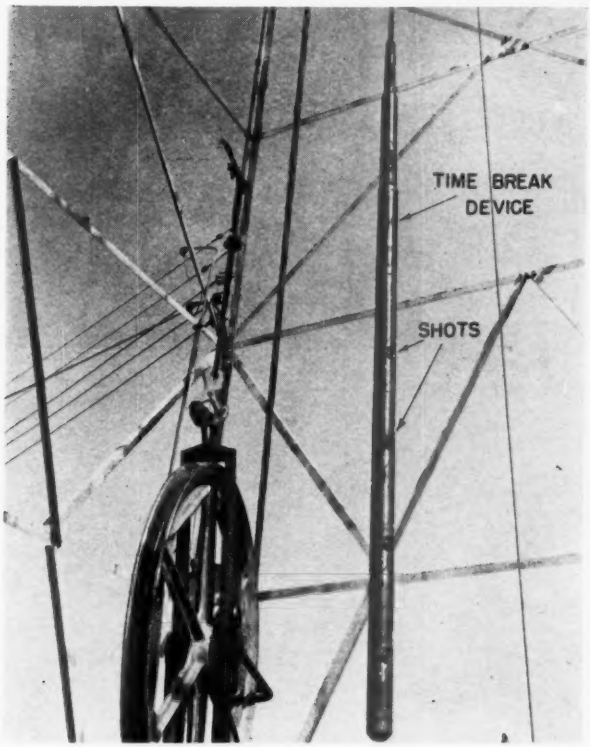

FIG. 4. Perforator gun used as a sound source.

ing on the side of the cable. A short length of aeroplane cable is spliced into the central support member of the main suspension cable. The aeroplane cable has a small steel ball swedged onto its lower end. The ball fits into a socket at the upper end of the geophone assembly, providing mechanical weight support. Latches clamp the cable loosely at the top and bottom of the geophone assembly. Pressure-proof electrical plug-in connections are provided for connecting the geophone to the appropriate cable conductors. With this arrangement, it is possible to attach or remove the geophone assembly from the cable in a matter of minutes when going in or out of the hole. When the geophone assemblies are removed, the link cable, with its mechanical and electrical take-outs, may be passed over the cable sheaves and reeled onto the winch of the logging truck in the conventional manner. No difficulty has been experienced in a large number of field operations using this rather unconventional but practical arrangement.

The geophone is preferably a pressure detector. Magnetostriction units are

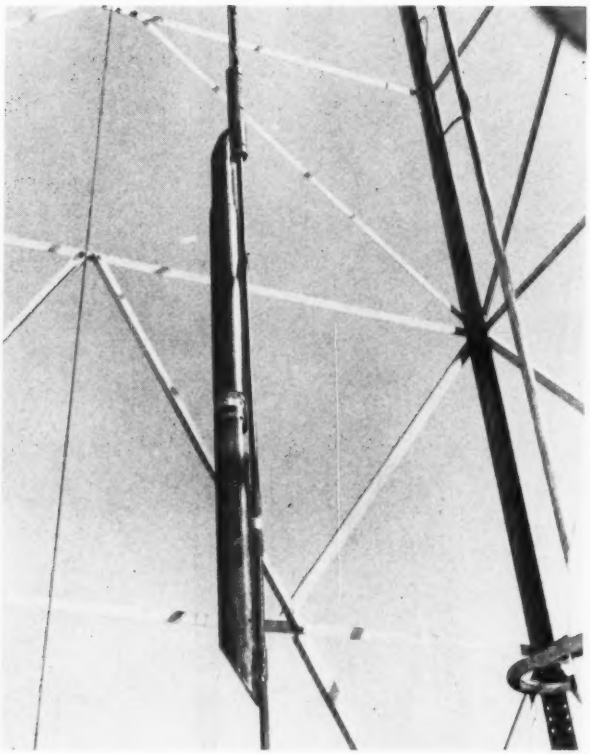

FIG. 5. Down-hole geophone mounted on side of cable.

used successfully and are chosen because of their simplicity, and immunity to bottom-hole temperature effects.

The truck carrying the equipment to the well may be an integrated unit carrying the main cable, the low velocity link, and all other necessary shooting and recording equipment. In another form, a relatively light panel truck is used to carry the link and the other special equipment to the well. The low velocity link is connected to the cable of the regular well logging truck by means of the so-called torpedo connection shown in Fig. 6. The torpedo will pass over the sheave wheels and onto the cable reel. Economy of equipment and wider operating range make the panel truck arrangement desirable in most areas. Other pertinent remarks regarding equipment will be made later in the discussion.

FIELD EXAMPLES OF RECORDINGS

A typical record made with the long interval method is shown in Fig. 7. The uppermost trace carries the time break. Traces 2 and 3 record the energy

from the geophones located 400 feet and 800 feet respectively above the gun. The two lowermost traces carry recordings from geophones set on the ground surface, 200 feet and 100 feet respectively from the well. In the example shown, geophones were also placed in a shallow hole at the 200-foot position, with the corresponding recording on traces 4 and 5. Some cross coupling is induced into the geophone circuits at the instant of shooting but is of short duration and does not interfere with the first arrival recordings.

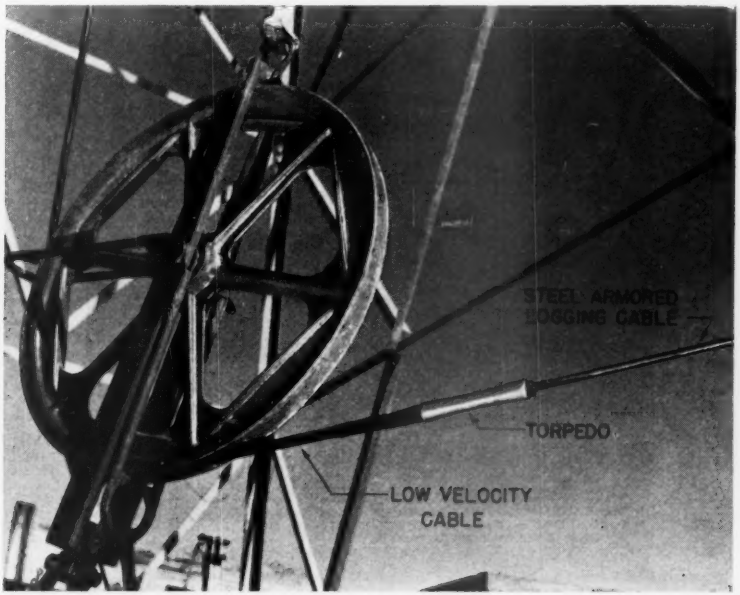

FIG. 6. Torpedo connection between regular steel armored cable and special low velocity cable.

Inasmuch as the interval travel times are relatively short, it is desirable to use a fast paper speed in the recording camera. The record shown was made at a paper speed of 48 inches per second, with timing lines appearing every two milliseconds.

Note that the arrivals on the down-hole geophone traces are picked to 0.2 millisecond, which is possible because of the remarkable sharpness of the breaks. The abrupt departure of the trace is still better appreciated when one remembers that the paper speed is four times that ordinarily used in seismograph practice The sharpness of the arrivals is due to the high frequency content of the detected energy.

In the examples shown, saturation of the amplifiers shortly after the first arrival prevents one from seeing the higher frequencies, e.g., 2,000 cps, which

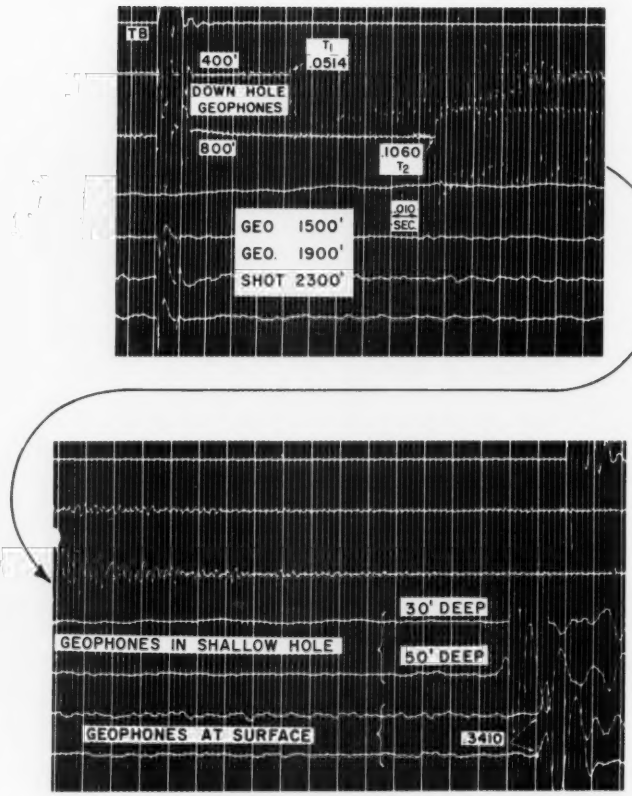

FIG. 7. Typical long interval record, including surface ties (Texas Gulf Coast).

are actually present. Detailed analysis of the problem will show that the frequency of the propagated energy increases as tamping or pressure is applied to an explosive discharge. It may be somewhat of a revelation, however, that energy with a frequency as high as 2,000 cps may be transmitted from a relatively low level sound source, such as a perforator gun, through as much as 800 feet of the earth.

Fig. 8 shows a recording of a deeper shot in the same hole. Here the surface traces are not in use. The sharpness of the down-hole arrival recordings is particularly evident in this example.

TABULATION AND COMPUTATION OF DATA

A desirable feature of the new method is the simplicity of computation. A sample tabulation of data of a typical survey is shown in Fig. 9. The gun and

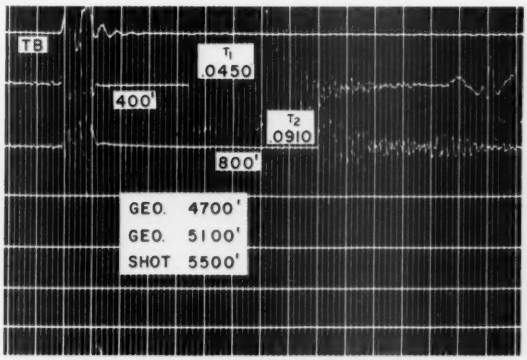

FIG. 8. Typical long interval record at greater depth (Texas Gulf Coast).

geophone depths are shown in the columns at the left. The column headed T_1 is the interval time from the gun to the lower geophone, while T_2 is the interval time from the gun to the upper geophone. T_2-T_1 is the interval time between the two geophones. Since a 400-foot interval of the hole is overlapped on the succeeding shot, it follows that T_1 of a given shot and T_2-T_1 of the next lower shot are measurements of time across the same identical interval of hole, and should give the same interval travel times.

The tabulation is simplified in the form shown in Fig. 10. The interval, depths are shown in the column at the left. The second column gives a reference to the record on which the interval is measured. The figures in the column headed T_i are the T_1 and T_2-T_1 times obtained for the same interval in two successive shots, as shown in the tabulation of Fig. 9. $\overline{T}_i$ is the average interval time.

A travel time measurement across the cased portion of the hole is obtained by recording on geophones at or near the surface and is the asterisked figure in the Total Travel Time (T_t) column.

Total travel time to any point in the hole is obtained by taking the surface tie time and adding the successively deeper interval times from the interval measurements. In effect, a running sub-total is carried for increasing depth. Average

	DEPTHS			TIME		
	G_2	G_1	SHOT	T_2	T_1	T_2-T_1
1.	700	1100	1500	.1140	.0552	.0588
2.	1100	1500	1900	.1096	.0544	.0552
3.	1500	1900	2300	.1050	.0506	.0546
4.	1900	2300	2700	.1016	.0510	.0506

FIG. 9. Tabulation of data.

INTERVAL	RECORD REF.	T_i	$\overline{T_i}$	T_t	$\overline{V}$	V_i
0 — 1500	1			* 2207	6790	
1500–1900	2	0544	0545	2752	6910	7340
	3	0546				
1900–2300	3	0506	0506	3258	7060	7900
	4	0506				

* INDICATES SURFACE TIE TIME

FIG. 10. Simplified tabulation of data.

velocity ($\overline{V}$) and interval velocity (V_i) are computed in the conventional manner. Because of the inherent simplicity of the method, it is seen that after the records are read, little effort is required to arrive at the desired results.

Fig. 11 is a chart showing total travel time, and average and interval velocity, presented in the conventional manner.

ACCURACY

Although the method is referred to as the long interval method, its principal objective is the measurement of total vertical travel time from a point at or near the

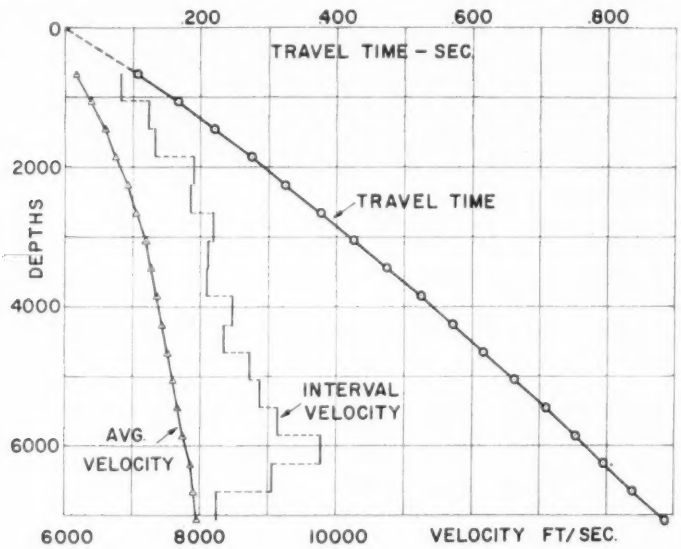

FIG. 11. Long interval velocity survey results (Texas Gulf Coast).

surface to various depths in the ground. With the long interval method, such measurements are possible to a remarkably high degree of accuracy.

Changes in bore hole diameter will have negligible effect on the interval time measurements when the interval is several hundred feet long.

The high frequency character of the propagated and detected energy is an aid in accurate measurement, provided the survey equipment is properly designed. The high frequency response of the magnetostriction geophone is excellent. The response of the associated amplifier system is essentially flat from 20 cps to 2,000 cps. Galvanometers with natural frequency of 2,000 to 3,500 cps are used for the recording.

It can be shown that since the records can generally be read to plus or minus 0.2 milliseconds, the probable error for 25 measurements of 400 feet each, covering 10,000 feet of open hole, is one millisecond. Even if records are read to the nearest one-half millisecond, the probable error would be only 2.5 milliseconds for 25 measurements.

Any interval method is susceptible to systematic error, which would accumulate with the summation of the individual intervals, and care must be taken to avoid such errors. The interval spacings must be cut accurately and can be held within inches. If the survey is made going down the hole, care must be taken to prevent slack in the interval cable by dropping below, and then pulling up to, the shooting depth.

Systematic error is avoided in the geophone-geophone interval measurement, this being a true interval measurement, provided the same type geophone, amplifier, and recording circuits are used for both. A correction at the time break may be necessary for travel time from the shot in the gun to the time break device at the upper end of the gun assembly. This correction is needed when the formation velocity is substantially different from the 17,000 feet per second velocity of the gun. As an example, the correction amounts to minus 0.35 milliseconds when the formation velocity is 8,500 feet per second and the shot is 6 feet below the time break device. Care should be taken in computing the correction in the case where the gun and time break device are in a low velocity bed only a few feet thick. Knowledge of approximate formation velocities, combined with reference to the electrical log for the type of formation, permits judicious selection of the velocity to be used in computing the correction.

COMPARISONS WITH CONVENTIONAL GEOPHONE SURVEYS

Comparisons with conventional geophone surveys in the same hole have been made in twelve wells through August, 1955. In several cases the check was very good; no attempt is made to provide an example since the slight differences in the curves would not be discernible. In other cases, differences up to approximately one percent have been noted. An example of one of the largest discrepancies encountered is shown in Fig. 12. This comparison was made in a deep West Texas well. Since the surface casing was set to a considerable depth, a

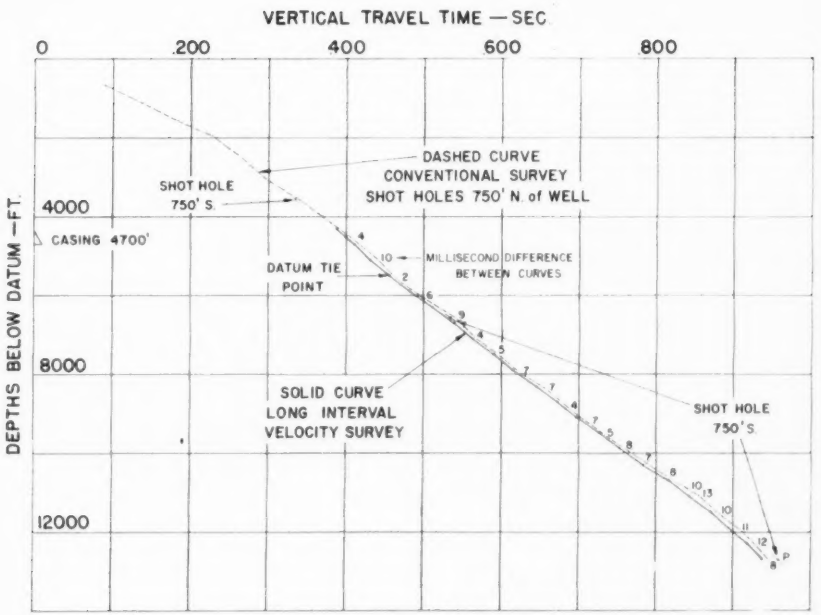

FIG. 12. Comparison of long interval velocity survey and conventional geophone survey in same well, illustrating discrepancies sometimes encountered (West Texas).

datum tie from datum plane to 5,500 feet was obtained by means of a dynamite shot in a shot hole at the surface and recording on the down-hole geophones below the casing.

The figures inserted along the curves are the millisecond differences in vertical travel time as obtained by the long interval and conventional geophone surveys. The differences noted here are fairly typical of the comparisons that have been made thus far, wherein a discrepancy has appeared, as to the tendency of the long interval survey to give both a shorter vertical travel time and a smoother curve.

It has been suggested that the tendency of the long interval method to measure a shorter vertical travel time is the result of a frequency effect since the long interval method operates at much higher frequencies than the conventional method; also, that the conventional results may be preferred for the reflection survey correction since the frequencies are then the same. In studying the problem, it is desirable to keep in mind that the frequency effect, if any, may be only an apparent one because of the problems associated with the low frequency first arrival detection at the greater depths.

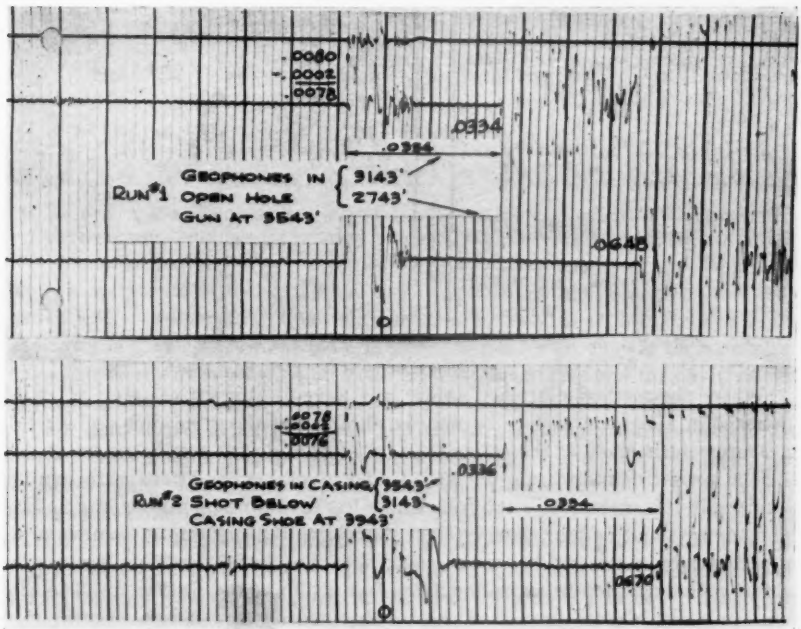

FIG. 13. Example of reliability of measuring interval time with geophones in casing when the shot is below the casing shoe. On Run No. 1 in open hole, time over interval 3,143′–3,543′ is .0334 sec/ft. On Run No. 2, same time is obtained over the interval through casing (Texas).

SURFACE AND DATUM TIES

As mentioned previously, interval measurements cannot, in the general case, be made in the casing. All interval velocity measuring methods share this drawback, as well as the resulting problem of obtaining a time tie across the casing to a point at or near the surface. Since this problem has several solutions, varying in effort and cost according to conditions at a particular well, it may be useful to describe briefly the various methods which experience shows to be effective.

It has been found that if the shot is placed below the casing, reliable interval time measurements can be made to geophones up in the casing. An illustration is given in Fig. 13. If the casing is shallow, one of the down-hole geophones may be placed below the weathering at the depth of the reference datum plane, with the gun below the casing shoe, as shown in Fig. 14. It is seen that the survey can start at datum and proceed downward in a simple series of stacked intervals, leaving the extreme surface geophones out of the setup and thus confining operations entirely to the bore hole. The depth to which datum ties can be obtained in this manner varies widely from well to well, depending on such factors as type of formations and rig noise level.

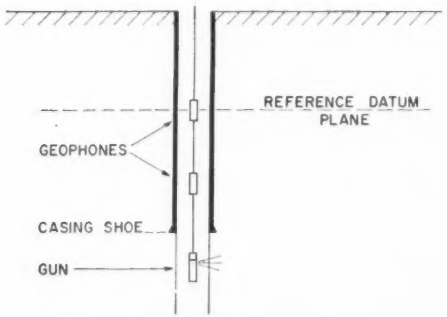

FIG. 14. Datum tie across casing using down-hole geophones.

Where the method described above fails, several alternatives remain, as illustrated in Fig. 15. A surface tie may be obtained at the same time an interval measurement is made at the casing shoe by recording with geophones set at the surface a short distance from the well. Under favorable conditions, a tie can be obtained in this manner to 2,000 feet. Under less favorable conditions, the tie can be made by shooting four shots or eight shots simultaneously from another type of perforator gun lowered below the casing shoe. Successful ties have been made in this manner to depths exceeding 4,000 feet, as illustrated in Fig. 16. The up-hole time from datum to surface can be obtained by exploding a blasting cap in the well at datum and recording on a surface geophone, as shown in Fig. 17. This up-hole time can then be subtracted from the surface tie time to obtain the desired datum tie time.

Where the casing is deep, or if other conditions are unfavorable, so as to pre-

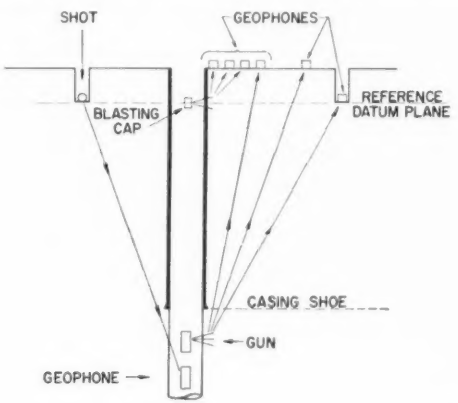

FIG. 15. Alternate methods of obtaining a datum tie across casing.

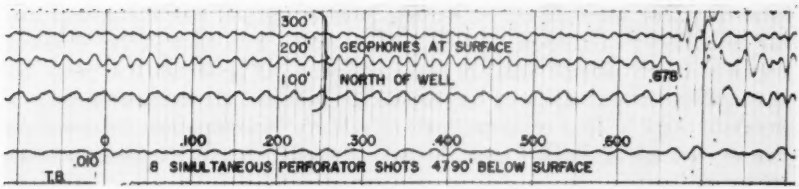

FIG. 16. Surface tie across casing from a depth of 4,790 feet, using a simultaneous firing multi-shot perforator gun. Conditions for recording were exceptionally good in this case (Mississippi).

clude a surface or datum tie by the simple reverse method, an alternative is to drill a hole of ordinary shot hole depth near the well and lower into it a geophone, as shown in Fig. 15. Datum ties from shots at greater depths are then possible, since the energy does not pass through the weathered layer and the environment of the geophone is generally more quiet.

For deep casing, a charge may be exploded in a shot hole near the well in the conventional manner and the energy detected in the well on the well geophones set below casing. The expense of such a single shot hole, which can be drilled at any convenient time beforehand, is relatively small.

To minimize errors in obtaining a datum tie, to dispense with all shot holes, and to confine all operations to the bore hole, the recommended procedure is to make the long interval survey in two or more runs as is commonly done with open hole logging methods.

CONCLUSIONS

The demand for accurate total travel time and average velocity information is steadily increasing. The economics of the industry require that the accelerated program of securing velocity information be accomplished without increasing the

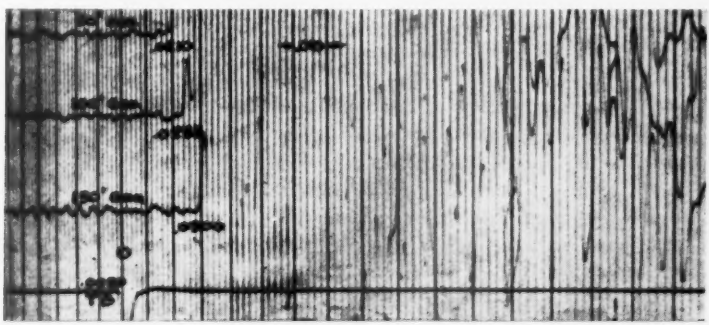

FIG. 17. Up-hole time, datum to surface, measured by means of a cap shot in casing in the well (West Texas). The shot was at 94 ft. depth below ground level, with surface geophones 50, 100, and 150 feet from the well.

total cost. The development of the long interval method was undertaken with the economics aspect being the first consideration. With each survey requiring only a relatively modest outlay of field equipment and personnel, it appears that the method has accomplished its purpose. In addition, the method provides an accurate check against other methods of velocity determination. As operations can be confined to the bore hole, the method is adaptable to all areas, including offshore.

ACKNOWLEDGMENT

The kind cooperation of the oil companies who have provided opportunities for the necessary field experimentation, and their courtesy in releasing the data given in this paper, is gratefully acknowledged. The author wishes to thank Schlumberger Well Surveying Corporation for permission to publish this paper, and also thanks the various members of the staff, especially Mr. Lyle Sorum and Mrs. Agnes Scholton, who have so ably assisted in its preparation.

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Kokesh, F. P., 1952, Development of a new method of seismic velocity determination: Geophysics, v. 17, p. 560–573.

GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 739–754, 9 FIGS.

APPLICATION OF CONTINUOUS VELOCITY LOGS TO DETERMINATION OF FLUID SATURATION OF RESERVOIR ROCKS*

WARREN G. HICKS† AND JAMES E. BERRY†

ABSTRACT

Recent studies of continuous acoustic velocity logs indicate that these logs may provide important assistance in differentiating gas, oil, and water saturations in reservoir rocks. In general, velocities are appreciably lower in sands carrying oil or gas than in water-saturated sands of otherwise similar character. Specific examples from field logs illustrate this application. Laboratory measurements have been made of acoustic velocity of synthetic and natural rocks. Published studies, both empirical and theoretical, of other workers concerned with the transmission of sound in porous media have been considered. All of these at least qualitatively confirm the conclusions drawn from field data.

INTRODUCTION

Several workers have presented both laboratory and theoretical studies of the various parameters which influence the speed of sound in porous media. Some have dealt with ordered packings of spheres while others have used samples of rocks occurring in nature. Because of the number of these studies reported on in the past few years, a wealth of information is now available concerning the factors controlling the velocity of sound waves in porous media.

Concurrent with this phase of research, logging systems have been developed which are capable of measuring the speed of sound waves in formations penetrated by wells. The velocity logging equipment developed at Magnolia Field Research Laboratories (Broding and Summers, 1952) is suitable for interpretative studies and continuous velocity logs have been run in a large number of wells by several companies. Since the prime objective of each of these wells is to produce oil, we shall be particularly concerned in this paper with the phase of log interpretation which attempts to discriminate between an oil reservoir, on one hand, and zones which will produce water or will produce little or no fluid on the other hand.

Among the parameters which will influence the velocity recorded at a particular zone are: (1) elastic constants of the grains comprising the framework of the rock, (2) type of cementing material bonding these grains, (3) grain density, (4) density of fluids contained in pores, (5) temperature, (6) pressure on rock skeleton, (7) pressures on fluids, (8) porosity, and (9) compressibility of fluids.

It is the purpose of this paper to show how the last four named of these parameters affect the velocity of sound in porous media and to illustrate by field examples how the log. interpreter can employ these relationships to his advantage.

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THEORETICAL CONSIDERATIONS

Compressibility of Saturating Fluid

Gassman (1951) has presented a theoretical solution for the speed of sound waves in a ***hexagonal*** packing of spherical grains with the pore spaces occupied by a liquid. This expression may be written:

$$V = \left[\frac{1}{\rho}\left(\frac{\alpha^*}{D^*}b_3^2 + 16\bar{c}\right)\right]^{1/2} \tag{1}$$

where

$$\rho = (1-\phi)\rho_g + \phi\rho_l$$

$$\frac{\alpha^*}{D^*} = \frac{1}{\dfrac{\phi}{B_l} + \dfrac{3(1-2\sigma)}{E}\left[(1-\phi) - \dfrac{12(1-2\sigma)\bar{c}}{E}\right]}$$

$$b_3 = 1 - \frac{24(1-2\sigma)\bar{c}}{E}$$

$$\bar{c} = \frac{1}{24\sqrt{2}}\left[\frac{2\pi E^2(\rho_g - \rho_l)gZ}{(1-\sigma^2)^2}\right]^{1/3}$$

and

ρ_g = density of grains, grams per cubic centimeter.
E = Young's modulus of grains in dynes per square centimeter.
σ = Poisson's ratio of grains.
B_l = bulk modulus of liquid in dynes per square centimeter. Bulk modulus is the reciprocal of compressibility.
ρ_l = specific gravity of saturating fluids.
ϕ = fractional porosity; for hexagonal packing assumed to be 0.26 or 26 per cent.
Z = depth in centimeters.
g = acceleration of gravity = 980 centimeters per second per second.
V = vertical compressional velocity in centimeters per second.

Gassman's equation describes a self-loaded system; that is, the pressure on the spherical grains is the weight of a column of such grains extended to the surface and the hydrostatic head on the fluid is the weight of a column of such fluid extended to the surface. The assumed pressures may be replaced by known pressures where available.

White and Sengbush (1953) have also developed a theoretical solution for the speed of sound waves in a *cubical* packing of spherical grains with a liquid occupying the pore spaces. This expression is:

$$V = \left\{ \frac{\dfrac{1}{\dfrac{1-\phi}{k_g} + \dfrac{\phi}{B_l}} + \left[\dfrac{\pi(\rho_g - \rho_l)gE^2Z}{16(1-\sigma^2)^2}\right]^{1/3}}{(1-\phi)\rho_g + \phi\rho_l} \right\}^{1/2} \tag{2}$$

where all symbols are the same as in the Gassman expression and k_g is bulk modulus of the grains in dynes per square centimeter. The fractional porosity, ϕ, for cubical packing is 0.476, or 47.6 percent.

A very important equation has recently been formulated by Brandt (1955). It applies to randomly packed, non-spherical particles, with variable porosity. For a saturated aggregate this expression may be written:

$$V = \frac{5.75(P_0 - cP_l)^{1/6}}{\phi^{1/2}[\rho_g - \phi(\rho_g - \rho_l)]^{1/2}k^{1/3}} \cdot \frac{[1 + 17.5B_l^{3/2}k(P_0 - cP_l)^{-1/2}]^{5/6}}{[1 + 26.3B_l^{3/2}k(P_0 - cP_l)^{-1/2}]^{1/2}} \tag{3}$$

where V is vertical compressional velocity in feet per second.

P_0 is the pressure on the frame of the rock in pounds per square inch;

P_l is the pressure on the liquid in pounds per square inch;

c is a constant near unity. c was evaluated by Brandt for a particular experiment and found to be 0.87.

k is a constant which is determined by the rock. It was evaluated experimentally for a particular sandstone core and found to be 10^{-7}.

B_l is the bulk modulus of the saturating fluid. In this equation the units are pounds per square inch.

The three equations may be used to evaluate theoretically the effects of changes in various parameters. Of particular interest are the effects of changing compressibility of the saturating fluids. Water is less compressible than the hydrocarbons. Hydrocarbon mixtures may have a wide range of compressibilities depending upon their composition, temperature, and pressure. Equivalent values were used for the parameters in each equation, even though, in some cases, this meant choosing values slightly different from those used by the authors in their original work. Values were assigned as follows: E, 10^{12} dynes/cc; σ, 0.20; ρ_g, 2.65 grams/cc; Z, 3.04×10^5 cm or 10,000 ft.; g, 980 cm/sec^2; P_0, 9,600 psi; and P_l, 4,330 psi. In the cases of hexagonal and cubical packings of spheres, porosites are fixed at 0.26 (26 percent) and 0.476 (47.6 percent) respectively. In Brandt's equation the porosity term may be varied. Two values, 0.26 and 0.476, were chosen but no variation was made in the values used for the elastic constants other than the compressibility of the saturating fluid. This permits a qualitative comparison of Brandt's results with those of Gassman and of White and Sengbush. The similarity of curves representing the three equations is illustrated in Fig. 1.

A further word of explanation of Fig. 1 is necessary. The term B_l, bulk modu-

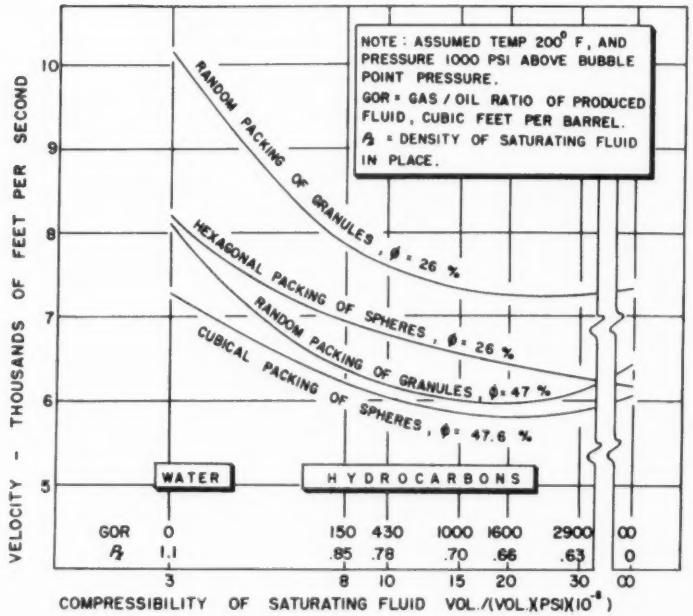
NOTE : ASSUMED TEMP 200° F, AND PRESSURE 1000 PSI ABOVE BUBBLE POINT PRESSURE.
GOR = GAS / OIL RATIO OF PRODUCED FLUID, CUBIC FEET PER BARREL.
ρ = DENSITY OF SATURATING FLUID IN PLACE.
RANDOM PACKING OF GRANULES, ϕ = 26 %
HEXAGONAL PACKING OF SPHERES, ϕ = 26 %
RANDOM PACKING OF GRANULES, ϕ = 47 %
CUBICAL PACKING OF SPHERES, ϕ = 47.6 %
WATER
HYDROCARBONS
VELOCITY - THOUSANDS OF FEET PER SECOND
10
9
8
7
6
5
GOR 0 150 430 1000 1600 2900 ∞
ρ 1.1 .85 .78 .70 .66 .63 0
3 8 10 15 20 30 ∞
COMPRESSIBILITY OF SATURATING FLUID VOL./(VOL.)(PSI)(10⁻⁶)

FIG. 1. Theoretical curves showing acoustic velocity through porous media as a function of compressibility of the saturating fluid.

lus of the saturating fluid, appears in the equations. In a sense this is the independent variable for the graphs in the figure. However, since compressibility is perhaps a more familiar concept for most people, compressibility was substituted for bulk modulus with proper regard for the reciprocal relationship between the two. Finally, it is evident that as compressibility increases the density or specific gravity of the liquid decreases and that the gas-oil ratio should increase. If the temperature and pressure above the bubble point pressure of hydrocarbons are specified there is a relationship between compressibility, density (specific gravity or API gravity), and gas-oil ratio. In Fig. 1, it is assumed that the temperature is 200° F and the pressure is 1,000 psi above bubble point pressure. Therefore, the additional scales showing density and gas-oil ratio along the abscissa are determined by this relationship (Elfrink, 1952).

Fig. 1 shows relatively high velocities when the saturating fluid is salt water with a compressibility of 3×10^{-6} psi^{-1}. The velocities decrease appreciably as the compressibility of the saturating fluid increases. The more compressible fluids may be considered to be hydrocarbons having the densities and gas-oil ratios shown. The curves are carried to the extreme case of infinite compressibility and zero density.

The important feature of these curves is that the velocity is depressed about 15 to 20 percent as the saturating fluid changes from water to oil. All three equations have the same trend of decreasing velocity as the compressibility of the saturating fluid is increased.

In making computations for the graphs in Fig. 1, we have assumed, for the sake of simplicity, that the pore spaces of the sands were completely saturated either with water or with hydrocarbon fluids. In nature, however, there is nearly always some water present in the pores of reservoir rocks. For a very interesting discussion of the effects of partial water saturation in hydrocarbon systems, the reader is referred to Wyllie, Gregory, and Gardner (1956).

Effects of Pressure

The effect of pressure on velocity is also of considerable interest. In equations (1) and (2) we can replace the terms $[\pi(\rho_0-\rho_l)gZ]$ by $C_1\ (P_0-P_l)$ where P_0 is overburden pressure, P_l is formation pressure, and C_1 is an appropriate constant. The significance of this substitution is that the pressure which enters into the computation of velocity is actually the *difference* between the *overburden* pressure determined by $\rho_0 gZ$, and the *hydrostatic* pressure, determined by $\rho_l gZ$. Similarly, in equation (3) the pressure which influences velocity is P_0-cP_l, where c is a constant near unity. This thesis has been verified by laboratory experiments. Data taken from pulse-transmission type apparatus similar to that described by Hughes, et al. (1951, 1952) are plotted in Fig. 2. The apparatus differed from that of Hughes in that the internal pressure as well as the external pressure on the sample could be controlled.

The pressure which enters into the velocity expression is the difference between these two pressures, P_0 and P_l. The velocity is relatively insensitive to the absolute magnitude of either. Thus, a sandstone having a normal pressure on its framework and an abnormally high pressure on its fluids will have an abnormally low velocity because the P_0-P_l term has become small. In similar fashion, a sand having an abnormally high pressure on its skeleton and a normal or low pressure on its fluid will have an unusually high velocity because now the P_0-P_l term has become large.

It is well to bear these facts in mind when examining data which have appeared in the literature. Hughes and Kelly (1952) have presented data which indicate that air-saturated cores under high pressure have higher velocities than the same cores when water-saturated and under the same pressure. Wyllie, Gregory, and Gardner (1956) have also reported similar results. Although these data are completely valid, they may lead to the erroneous conclusion that natural formations saturated with compressible fluids have higher velocities than those saturated with less compressible fluids. These laboratory data cannot be considered as typical of pressure distributions occurring in the earth. In these experiments, the cores and their contained fluids were both subjected to the pressure on the flexible jacket surrounding the core. In the case of one hundred percent

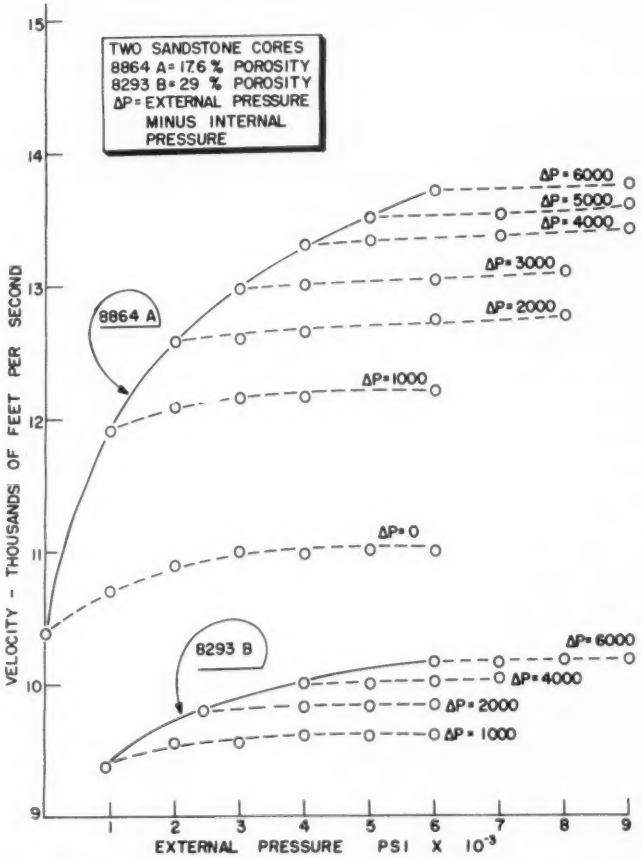

Fig. 2. Laboratory measurements of two sandstone cores showing acoustic velocity as a function of the difference between external and internal pressure.

water saturation, the fluid was at approximately the same pressure as the rock, therefore $P_0 - P_i$ was near zero and the wave velocity was low. However, in the case of the air-saturated cores, P_i was near zero and $P_0 - P_i$ is essentially the same as the pressure on the jacket. In this case, the velocity function increased rapidly with pressure. Although this apparent discrepancy is pointed out by Wyllie, et al. (1956), the phenomenon is emphasized here because it is vital to the conclusions reached in this paper.

In nature, the pressure on the rock framework and the pressure exerted on the fluids contained in the pores of the rock may or may not be "normal" for a given depth. For example, a loose sand overlain by a thick competent bed may

have a framework pressure less than the weight of overburden above it. The relative position of the surface outcrop may control the hydrostatic pressure in an aquifer. In an aquifer of limited lateral extent and having no surface outcrop the fluid pressure may be either more or less than that of a column of brine extending to the surface. Abnormally high rock pressures and fluid pressures often are developed around salt domes.

Porosity

Brandt's (1955) equation predicts a decrease in velocity with an increase in porosity. This effect has been observed in our laboratory. Sandstone cores were obtained from three different wells, one in Hardeman County, Texas, one in Sumatra, and one in Colombia. The Texas cores were of Pennsylvanian age; the other two were Tertiary. The cores, one inch in diameter and varying from about one and a half to two inches in length, were saturated with 5,000 parts per million salt water. Saturation values were 100 percent except in some of the less permeable samples in which saturation was as low as 97 percent. Velocity measurements were made with a rock framework pressure of 6,000 psi and atmospheric internal pressure. The cores represent a range in porosity from about 3 to 30 per cent. Velocity versus porosity data are plotted in Fig. 3.

It can be seen in Fig. 3 that a plot of Equation (1) from Wyllie, Gregory, and Gardner (1956) fits the laboratory data fairly well. This equation may be written

$$\frac{1}{\overline{V}} = \frac{\phi}{V_{sw}} + \frac{1-\phi}{V_{ss}} \tag{4}$$

where

V_{sw} = salt water velocity,
V_{ss} = sandstone velocity, and
$\overline{V}$ = time-average velocity.

In plotting this equation V_{sw} was assumed to be 5,000 ft/sec, and V_{ss} was assumed to be 19,500 ft/sec. The latter value appears to be a little too high. Although the cores measured were described as being sandstone, no attempt has been made to determine the cementing agents or other impurities in them. The impurities may be responsible for the velocity values being lower than expected for porosities below 10 per cent.

Conclusions

In a given formation, the velocity variation one may expect from a maximum change in compressibility of the saturating fluid is of the order of 15 to 20 percent. The velocity variation one may expect due to changes in overburden and hydrostatic pressures corresponding to depths normally encountered in petroleum exploration is some 20 to 30 percent. The velocity variation from porosity changes over the range from 3 to 30 percent was found to be about 60 percent; variations of 100 percent over a greater range of porosity values are conceivable.

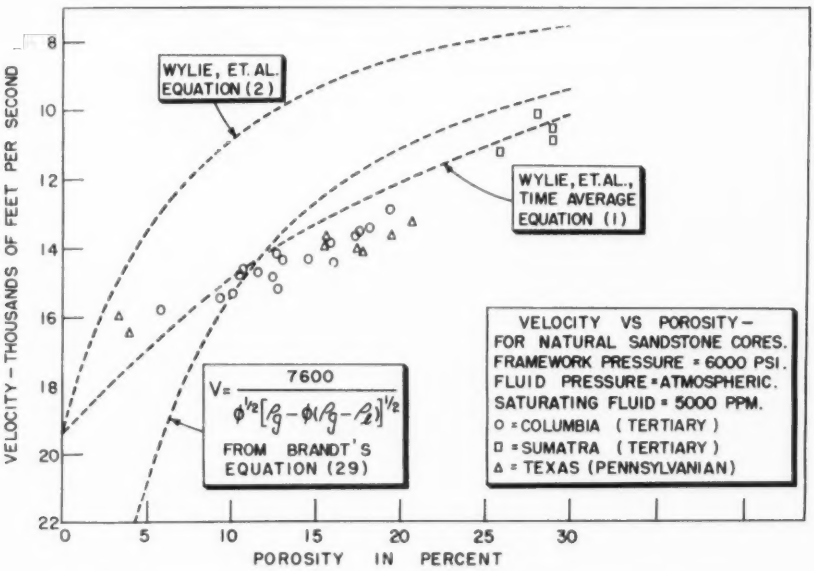

FIG. 3. Laboratory measurements of a number of sandstone cores from three areas showing acoustic velocity as a function of porosity.

It is generally reasonable to assume that both hydrostatic and overburden pressures are constant throughout the entire vertical extent of any given reservoir penetrated by a borehole, regardless of any variations in the porosity of the reservoir rock. In such a reservoir the velocity of sound will decrease with increased porosity and with increased compressibility of the saturating fluid. From a practical standpoint, it can be said that velocity variations caused by changes in compressibility of the saturating fluid are most easily observed in formations of high porosity. As porosity decreases, these variations tend to become second order effects.

APPLICATION TO LOG INTERPRETATION

High Porosity Sands

In the Cenozoic formations along the Gulf Coast, sands of generally high porosity are interbedded with shales and occasional hard, calcareous sandstones. The velocity log through these formations is rather monotonous, with water sands typically having a velocity in the neighborhood of 2,000 ft/sec higher than that of the adjacent shales. Hard, calcareous sands may have velocities of about 5,000 ft/sec higher than the adjacent shales.

Fig. 4 illustrates a comparison of velocity and resistivity logs in the upper

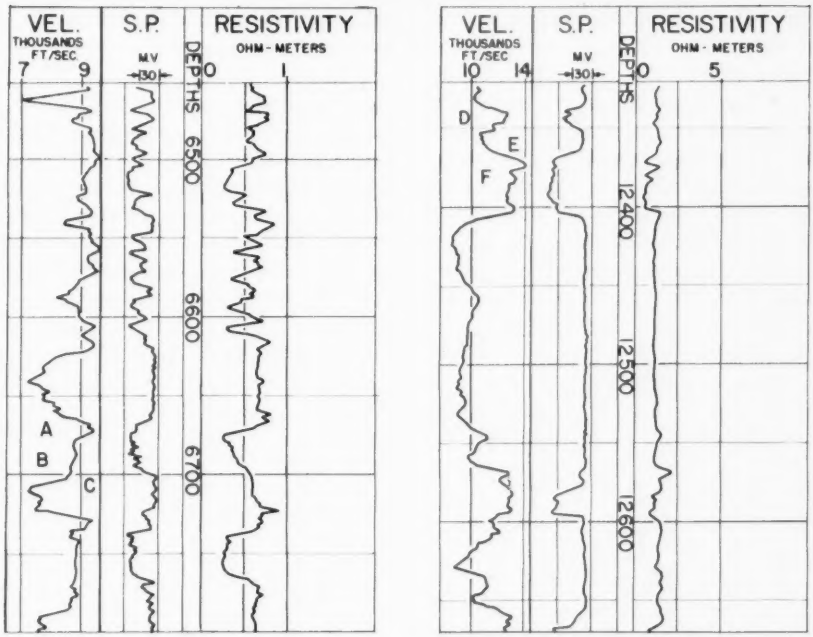

FIG. 4. Velocity and electric log comparison of upper Miocene section, Louisiana Gulf Coast, Ship Shoal area.

Miocene section penetrated in a well in the Ship Shoal area of the Gulf of Mexico, off the Louisiana coast. In general, an anti-correlation is observed between the *SP* curve and velocity. Where the *SP* curve indicates sand by a deflection to the left the velocity is high; when shale is indicated on the *SP* the velocity is low. Two sections of alternating shales and water-bearing sands are shown, one from 6,450–6,800 feet and another from 12,320–12,670 feet. The velocity log is shifted toward higher velocity in the deeper zone as might be anticipated from consideration of pressures. In particular, zone *A* is indicated as a sand from the leftward deflection of the *SP* curve. The velocity in zone *A* is about 9,200 ft/sec. Zone *B* is shown by the undulations of the *SP* curve to be partly sand and partly shale. Shale generally depresses the velocity and here we find that the velocity has decreased to about 8,700 ft/sec. Bed *C* appears to be a fairly pure shale zone, and here we observe that the velocity has decreased to 7,400 ft/sec. Similarly in the deeper section, zone *D* is a sand of about 12,200 ft/sec, zone *E* is a shale of about 10,500 ft/sec, and zone *F* is another sand having a velocity about 13,000 ft/sec. This general correlation of high velocity sands and low velocity shales exists in most instances, although some exceptions are found in young formations at shal

low depths. Resistivity curves opposite sands in this illustration give extremely low resistivities, indicating that these sands are quite porous and filled with very salty water.

Several writers (Vogel, 1952; Summers and Broding, 1952) have observed correlations between velocity logs and resistivity curves. These correlations are generally evident, and in some cases striking. In hard limestones both resistivity and velocity are high; in shales both resistivity and velocity are low. However, in the upper Miocene of the Louisiana Gulf, the water sands are commonly less resistive than the adjacent shales, although the water sand velocities are usually higher. Thus, a degree of anticorrelation exists in this particular case. A more dramatic form of anti-correlation exists when the velocity in a sand is anoma-

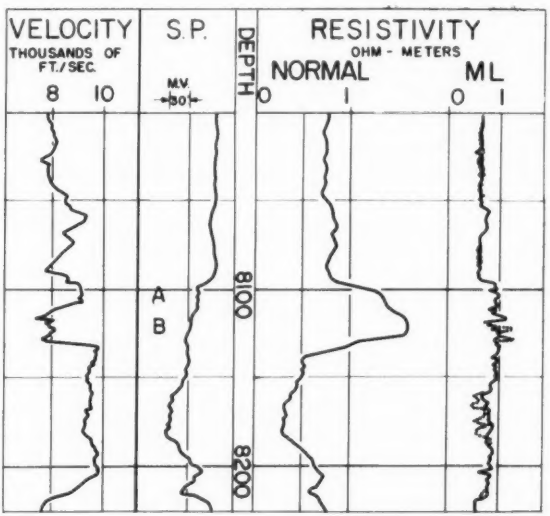

FIG. 5. Velocity and electric log comparison, upper Miocene section, Louisiana Gulf Coast, Eugene Island area.

lously low and the resistivity is high. This is exactly the anti-correlation we are searching for because this is virtually certain to be a porous, hydrocarbon-saturated zone. Fig. 5 illustrates this anti-correlation. These logs are from a well in the Eugene Island area of the Louisiana Gulf Coast and show a thick upper Miocene sand from 8,098 to 8,217 feet in depth with low porosity (A) at the top, followed by 22 feet of porous sand saturated with oil or gas (B) with a transition to water saturation in the lower part of the sand. The hydrocarbon-water contact is indicated by both the resistivity and velocity log at the base of zone *B*, although *SP*, Microlog and normal curves indicate that possibly 100 percent water saturation does not occur above 8,157 feet. The velocity in the water zone is around

9,500 ft/sec; in the pay zone it is about 7,900 ft/sec. This velocity depression is at least of the order of magnitude predicted by theory.

Another velocity log interpretation study is illustrated in Fig. 6. The section shown here is middle Miocene and the well is located in the West Cameron Area of the Louisiana Gulf Coast. Typical water sand response is shown in zone *E*, where the velocity is 10,000 ft/sec and all curves read values normally associated with water sands. In zone *A*, by contrast, the velocity is only 8,500 ft/sec. Moderate *SP* development, high resistivity, fairly low gamma-ray activity, and very high neutron response, all suggest hydrocarbon saturation which, in this case, is probably gas. Zone *B* looks similar to pay zone *A* on all curves except velocity, which reveals the presence of a thin, high velocity layer. This is therefore interpreted as a zone of low porosity. Zone *C* is possibly 8 feet of additional pay. Zone *D* is characterized by unusually high velocity and is interpreted as a very tight, hard sandstone.

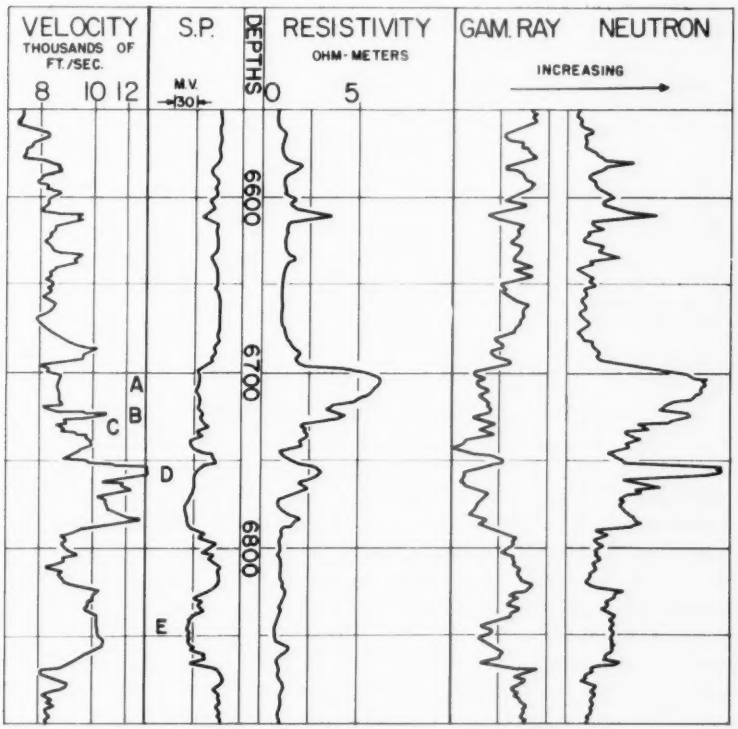

FIG. 6. Velocity, electric, and radioactivity log comparison of middle Miocene section, Louisiana Gulf Coast, West Cameron area.

Fig. 7 illustrates an idealized log response in typical Gulf Coast Miocene sections. In shales, we would expect low velocity, low resistivity, low neutron count; in gas sands, low velocity, high resistivity, high neutron count; in tight sands, high velocity, high resistivity, and high neutron count; in oil sands, low velocity, high resistivity, intermediate neutron count; in water sands, fairly high velocity, low resistivity, and intermediate neutron count.

Shaly Sands

Several excellent articles (Poupon, Loy, and Tixier, 1954; and Perkins, Brannon, and Winsauer, 1954) have appeared in the literature regarding interpreta-

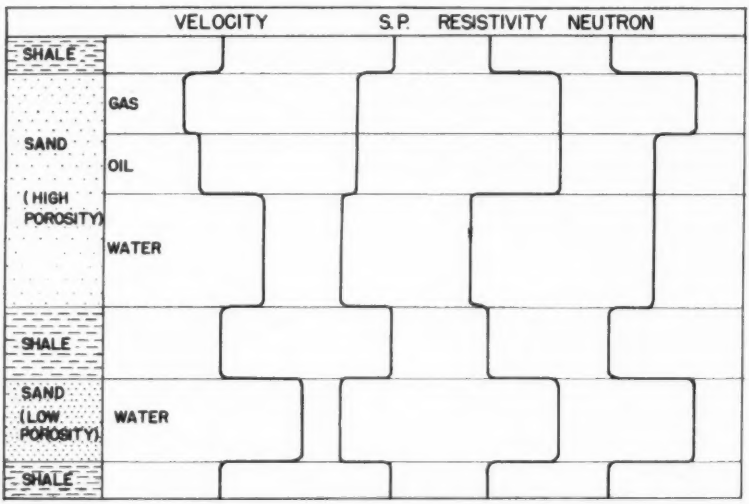

Fig. 7. Idealized logs of Miocene sands and shales.

tion of electric logs in reservoir sands containing shale. A complete discussion of the difficulties involved here is beyond the scope of this paper. However, the crux of the problem is that the resistivity index of a sand may be much lower for a shaly oil sand than for a similar clean sand. A portion of this difficulty arises because when the shale exists in very thin layers, the resistivity measuring current may be concentrated in the more conductive shale, and the oil sand tends to be by-passed in the resistivity measurement. The anisotropy of the electrical properties of the sandwich distort the field of investigation of resistivity logs. The velocity signal is a vertical measurement. No zone may be by-passed, but in the case of a sequence of thin layers, the total travel time recorded is the sum of each incremental travel time. Generally, the shale contained in a sand will tend to depress the velocity, but only in proportion to the actual shale present. One

additional feature which simplifies interpretation of velocity logs is that the velocity log is completely insensitive to any bed which is not within the six-foot vertical interval separating the sound source and receiver. Thus, any bed that is at least six feet thick yields an accurate velocity measurement, and no adjacent bed above the transmitter or below the receiver can make any contribution to the velocity log.

The Permian Delaware sand of West Texas is a notorious example of the difficulties of electric log interpretation in shaly or "dirty" sands. The evaporite

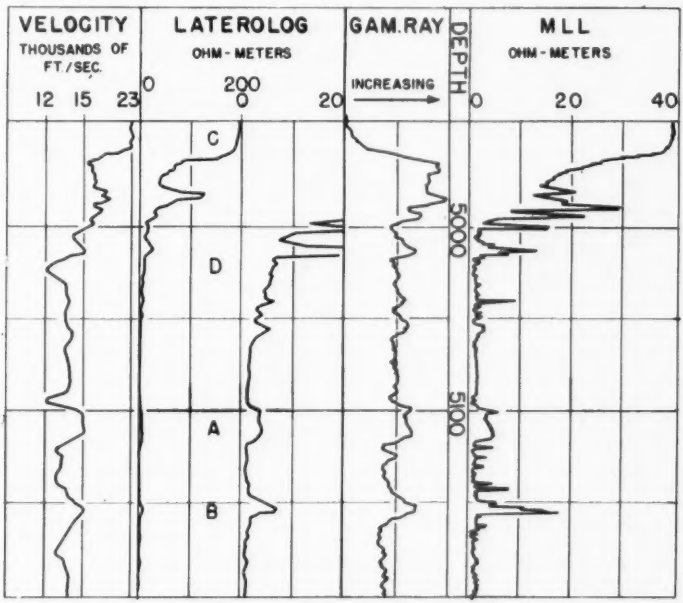

FIG. 8a. Velocity, electric, and radioactivity log comparison, Delaware Basin. Well No. 1.

section above the Delaware contains salt beds, so the drilling fluid is usually saturated with salt. The Delaware sand, where oil is present, is typically a recurring sequence of oil sand, water sand, shale, oil sand, water sand, etc. The thickness of each of the individual sand and shale beds may be of the order of inches. Fig. 8a and 8b present logs from two wells in the Delaware Basin. These wells are about 1 mile apart. Zone *C* is anhydrite, underlain by a black, calcareous, highly radioactive shale extending downward to zone *D*. Zone *D* is the uppermost portion of the Delaware sand. This sand section, interrupted by occasional thin beds of shale (as at *A* and *B*) extends downward through the remainder of the

logged intervals. Correlation between Wells No. 1 and No. 2 is established by the base of the anhydrite and by the persistence of the two shale beds at *A* and *B*. Well No. 1 (Fig. 8a) made water with some very light shows of gas on drillstem tests. Production casing was not set, and the well was abandoned. Well No. 2 (Fig. 8b) was completed from an interval in zone *D* flowing 207 barrels of oil per day with gas-oil ratio 6,000:1. The Laterolog of Well No. 1 records an apparent

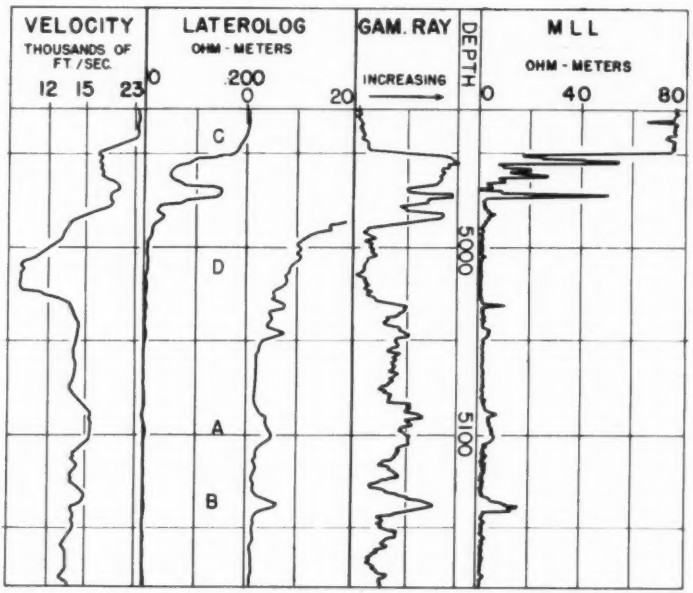

FIG. 8b. Velocity, electric, and radioactivity log comparison, Delaware Basin. Well No. 2.

resistivity of about 6 ohm-meters in zone *D*, while the apparent resistivity of the same zone in Well No. 2 is 8 to 10 ohm-meters. The minimum velocity recorded in zone *D* in Well No. 1 is 12,000 ft/sec and the average about 13,000 ft/sec; in Well No. 2 the average is about 10,500 ft/sec. It may also be observed that the Microlaterologs suggest higher porosity and the gamma-ray logs "cleaner" sand (lower clay content) in the producing well than in the dry hole.

Low Porosity Formations

In the previous figures porosity development in the better sands has been greater than 20 percent. When we come to the less porous rocks we find that the compressibility effect on velocity is attenuated. Whereas in sands of 30 percent

porosity we could expect that the saturating fluid would influence the velocity by 2,000 ft/sec, in rocks of 10 percent porosity this effect may be attenuated to 500 ft/sec, and probably becomes negligible.

The compressibility of the saturating fluids is an important factor in determining the velocity of sound in reservoir rocks of high (20 to 30 percent or more) porosity. In rocks of low porosity, the compressibility of the saturating fluid be-

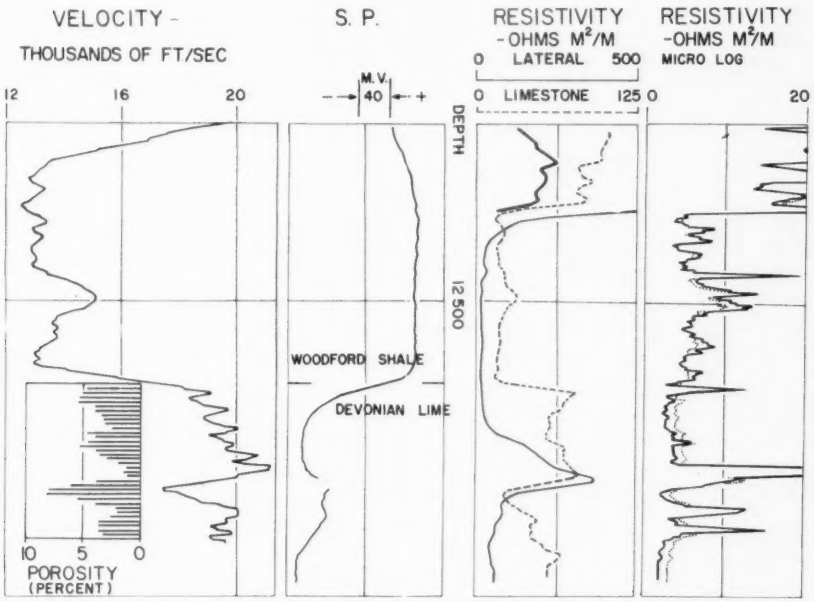

FIG. 9. Velocity and electric log comparison, Midland Basin. Lower left insert shows porosity from core analysis.

comes much less significant and the dominant factor is the rock itself. The velocity log in low porosity formations, therefore, finds its greatest application in distinguishing extremely compact formations from those containing fluid. Fig. 9 is a log of a well in the Midland Basin of West Texas, completed through perforations in the Devonian lime for 401 barrels of oil per day with gas-oil ratio 500:1. It will be observed that velocities are quite high in this limestone. Porosity values shown represent a six foot running average. As previously mentioned, six feet is the spacing between sound source and detector in the continuous velocity log. A reasonably good correlation between the porosity data and the velocity log is apparent. The electric log "limestone curve" and Microlog are correlated with the porosity and velocity logs.

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UNUSUAL REFLECTION EVENTS IN OFFSHORE SEISMIC WORK*

L. G. ELLIS† AND A. C. WINTERHALTER†

ABSTRACT

A number of unusual reflections were recorded during a reflection seismograph survey by the Sun Oil Company in the Gulf of Mexico. These reflections are such as to indicate horizontal travel paths. A limited amount of work was done to try to determine the nature of the reflecting sources. Although conclusive evidence as to their exact nature was not obtained, this work indicates the sources are associated with rather small areas of the Gulf floor. Sonic depth finder recordings over some of these areas can be interpreted as indicating they are small silt filled depressions.

INTRODUCTION

During a reflection seismograph survey by the Sun Oil Company off Padre Island in the Gulf of Mexico in the early part of 1951, some unusual reflections were recorded. The stepouts of these reflections across the records are such as to suggest that the travel paths were horizontal or nearly horizontal. These reflections were recorded using pressure type detectors and straddle spreads with the detectors extending 1,200 ft on each side of the shot point. Shoran was used for position location.

Seismograph lines in a limited area where such records were obtained are shown in Fig. 1. Within the area shown in this figure, there are at least eight different sources of these reflections. These sources are approximately located by the small circles. The smaller areas marked "*A*" and "*B*" and outlined by the dotted rectangles were selected for special study.

DISCUSSION OF RECORDS AND METHODS OF LOCATING REFLECTING SOURCES

Area "*A*," which centers about ten miles from shore in water approximately 90 ft deep, is shown in detail in Fig. 2. The most striking series of records was recorded along "*K*" line in this area. These records, which are shown in Fig. 3, indicate reflections from three different sources. These reflections are numbered 1, 2, and 3. The number 3 reflection does not line up across the records in the figure due to the fact that this reflection was recorded at record times in excess of six seconds while the camera was slowing down. Reflections from these three sources recorded on the north-south "*L*" line are shown in Figs. 4 and 5.

In order to obtain the approximate locations of the reflecting sources, perpendiculars were drawn to the seismograph lines through the detector positions recording the minimum reflection times. The intersections of perpendiculars

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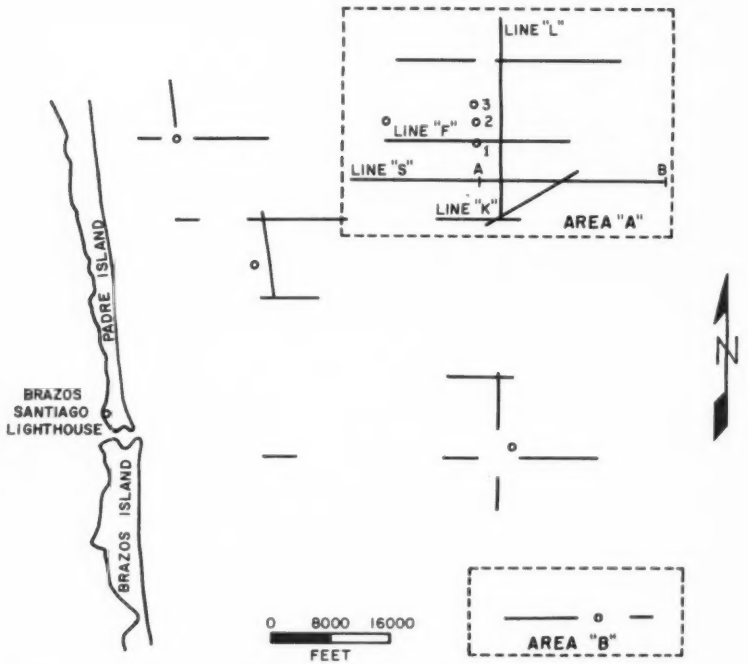

FIG. 1. Seismograph lines in the Gulf of Mexico in the vicinity of areas of unusual reflection events.

identified as being associated with reflections from the same source gave the approximate location of the source.

Apparent propagation velocity was obtained by plotting a time-distance curve using data from reflections from source number 1 received at locations from "*A*" to "*B*" on line "*S*" as shown in Fig. 1. This plot is shown in Fig. 6. The slope of the line through the plot of these data corresponds to a velocity of 4,940 ft /sec, and, although no water temperature or salinity measurements were made during this portion of the work, it is regarded as a reasonable velocity for reflection paths within the water body. Calculations based on published data (Adams, 1942, p. 872–878) indicate that this velocity is the approximate velocity for sound in sea water of the average salinity of 35 parts per thousand at a temperature of 16°C.

Using a velocity of 4,940 ft/sec and reflection times to various detector locations, limiting arcs were drawn in an effort to check the locations and to define the boundaries of the reflection sources. It was not possible to define the boundaries by this method. This failure was attributed to the following: (1) it was difficult and at times impossible to pick the initial points on many of the reflections since

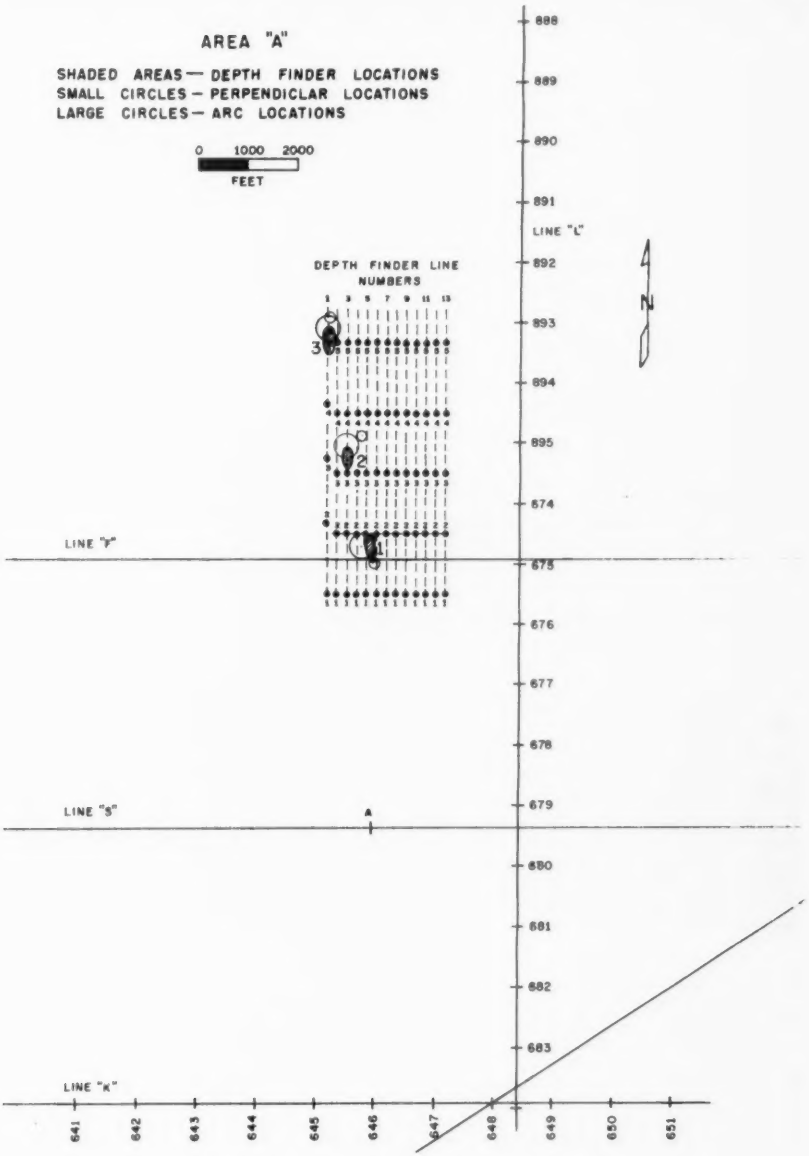

FIG. 2. Seismic and sonic depth finder lines in "*A*" area.

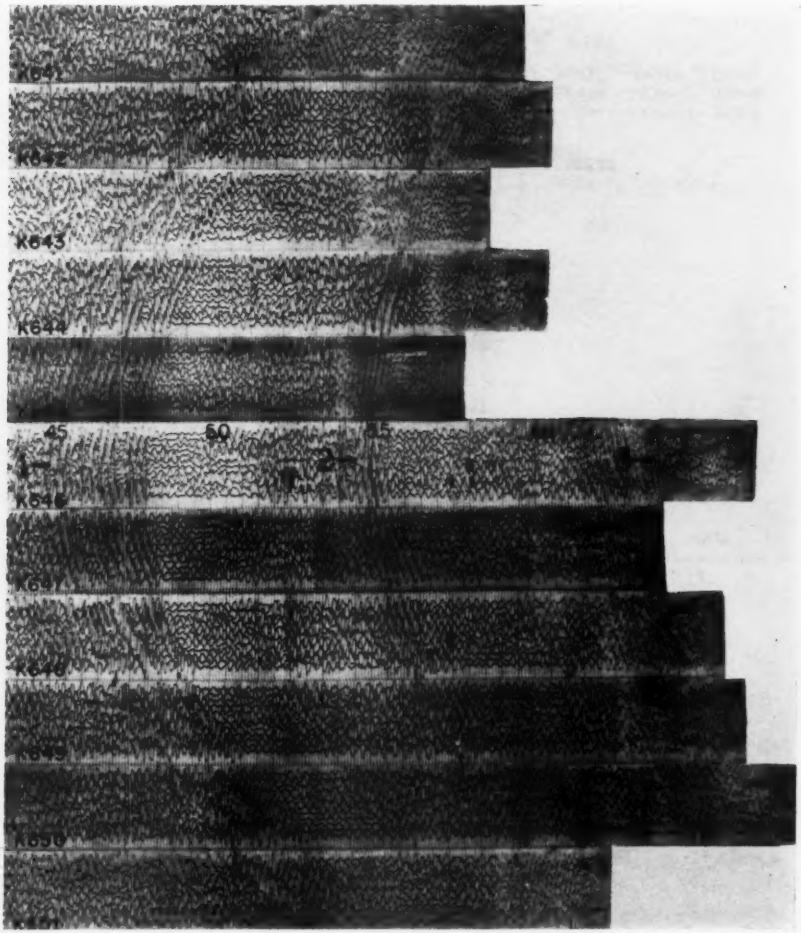

FIG. 3. Seismic records along "K" line "A" area showing unusual reflection events.

they are weak and obscured by normal reflections or other energy returns, and (2) the dimensions of the reflection sources are apparently of the order of magnitude of the limits of accuracy of the surveyed locations of the shot points and detectors. Nevertheless, the groupings of the arcs were such as to indicate the general locations of the sources as shown by the large circles in Fig. 2.

During the course of this work, it was decided to cover the area with a sonic depth finder in order to try to locate any abnormalities in the Gulf floor over these locations. Accordingly, depth finder records were obtained on thirteen parallel

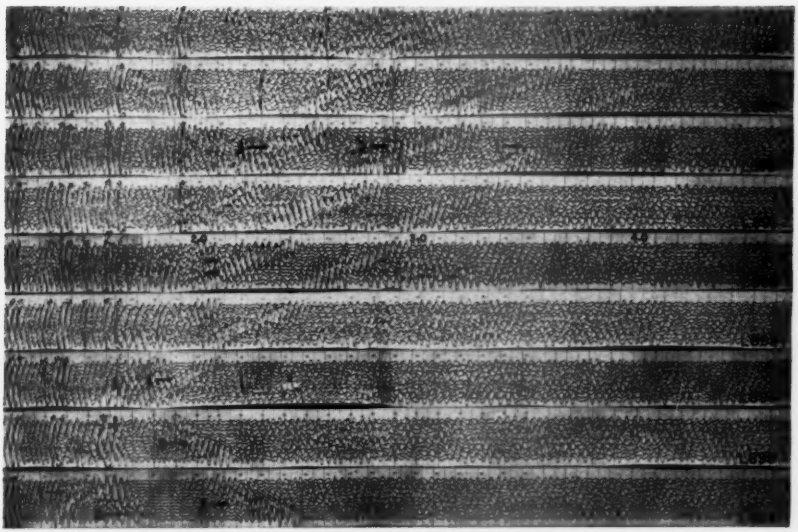

FIG. 4. Seismic records along "*L*" line "*A*" area showing unusual reflection events.

north-south lines and on three east-west lines, each about 5,000 ft long. The depth finder used in this work was a Type DR-3 Bendix Marine depth finder operating on a frequency of 50 kc. The locations of the north-south lines are shown in Fig. 2. The east-west lines are not shown because of the possibility of the figure becoming illegible due to crowding. However, one was located ap-

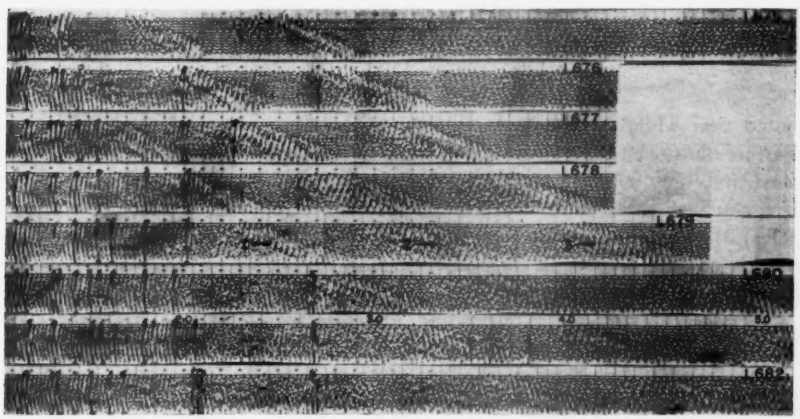

FIG. 5. Seismic records along "*L*" line "*A*" area showing unusual reflection events.

proximately through the points numbered "2" on the north-south lines, another was located approximately along seismic line "*F*," and the third was located half way between these two lines.

The depth finder records revealed three irregularities approximately over the three positions previously determined. Each irregularity took the form of a slight widening of the depth finder trace. Such a widening is usually attributed (Adams, 1942, p. 545–571) to the thickening of the mud bottom or to a *soft spot* in the bottom. A series of these depth finder records is shown in Fig. 7. It should be

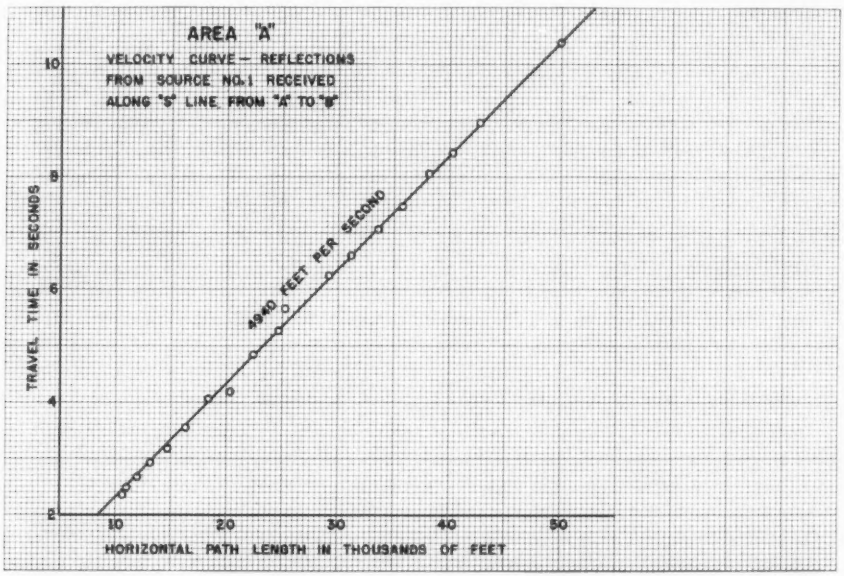

FIG. 6. Time-distance curve from data obtained from reflections from source number 1.

noted that while the north-south depth finder lines 1, 3, and 5 and the two southernmost east-west lines showed these irregularities, the northernmost east-west line, lines 2 and 4, and the remaining north-south lines showed no such irregularities. From these depth finder records, it appears that the areas of interest are rather small. It is possible, however, that the reflection returns are associated with an area in each case which includes part of the area of slope of the Gulf floor into the *soft spot* area. It is also possible that the greater portions of the reflecting sources are buried and, therefore, would not be entirely revealed by the depth finder.

The results of all three methods of locating the reflecting sources are shown in Fig. 2. The agreement of the locations by the various methods is considered good in view of the problems involved. The locations determined by the depth

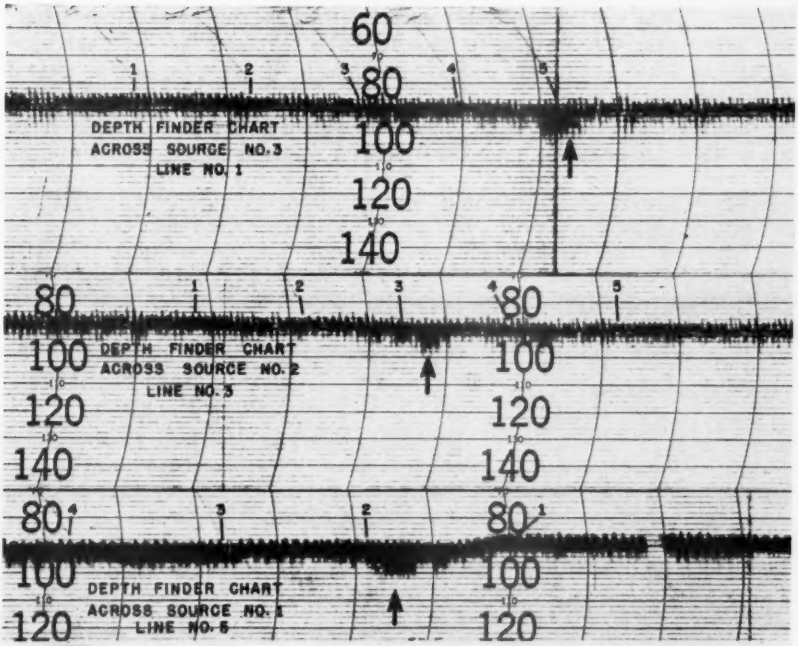

FIG. 7. Sonic depth finder charts across reflection sources in "*A*" area.

finder, however, are undoubtedly the most accurate if we concede that the reflection sources are associated with the *soft spot* areas.

Immediately following reflection number 1 in Fig. 3 are two additional reflections. The authors have not been able to explain these reflections to their satisfaction; so they will not attempt any discussion of them except to say that they appear to be associated with source number 1.

In the "*B*" area, there is only one reflecting source. Seven depth finder lines were run in the vicinity of this source. The records show a pronounced widening of the trace on three of these lines over the reflecting source as did the records over the sources previously discussed. The depth finder records on these three lines are shown in Fig. 8, and the locations of the lines are shown in Fig. 9. Fig. 10 shows a contour map of the Gulf floor which is based on data from the seven depth finder runs. The *soft spot* area, as revealed by the depth finder, is shown cross hatched.

EFFORTS TO DETERMINE NATURE OF REFLECTING SOURCES

An effort was made to obtain additional information as to the nature of the reflecting sources by refraction shooting. Two refraction fans were shot over

sources 1, 2, and 3 in "*A*" area. The distances from the shot points to the detector stations ranged from 2,000 to 5,000 ft. These refraction fans were arranged so that the distances from the detector locations to the reflecting sources ranged from zero to approximately 1,600 ft. The sources, of course, were always between the shot point and the detectors. These fans should have revealed the presence of any large masses having appreciable velocity contrasts to the velocities of the

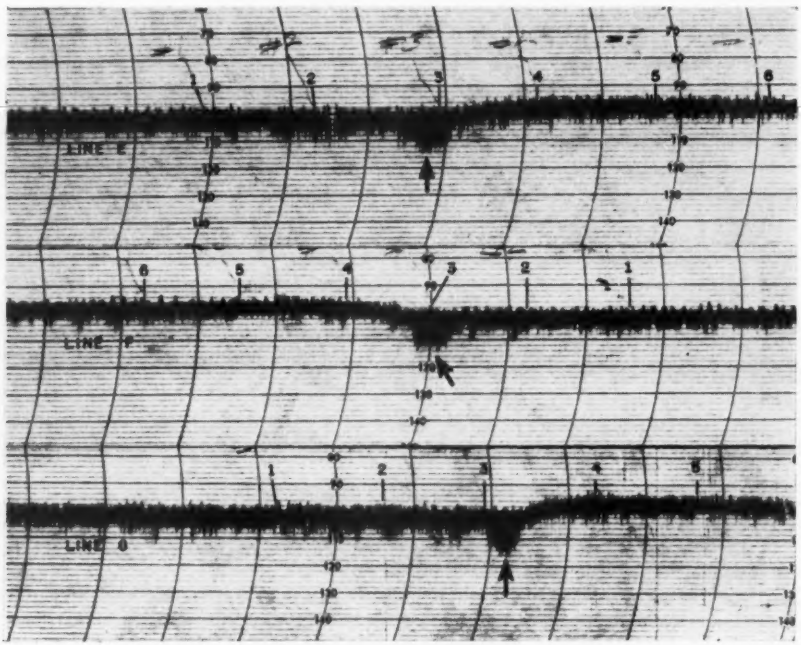

FIG. 8. Sonic depth finder charts across reflection source in "*B*" area.

surrounding sediments located just below the Gulf floor in the vicinity of the sources. No evidence of any such masses was found.

The depth finder results previously discussed led to the suggestion that the so called *soft spots* might be associated with artesian water flows into the Gulf and that the reflections might be due to velocity contrasts above the *soft spots* caused by differences in specific gravity and temperature between the surrounding water and the artesian flows. To check this hypothesis, measurements of temperature and specific gravity of the sea water were made in the vicinity of a reflecting source in another area located considerably to the north of sources 1, 2, and 3 and not shown in any of the figures. These measurements were made in a grid pattern over a limited area with separations of 300 to 600 ft and in a grid pattern over a

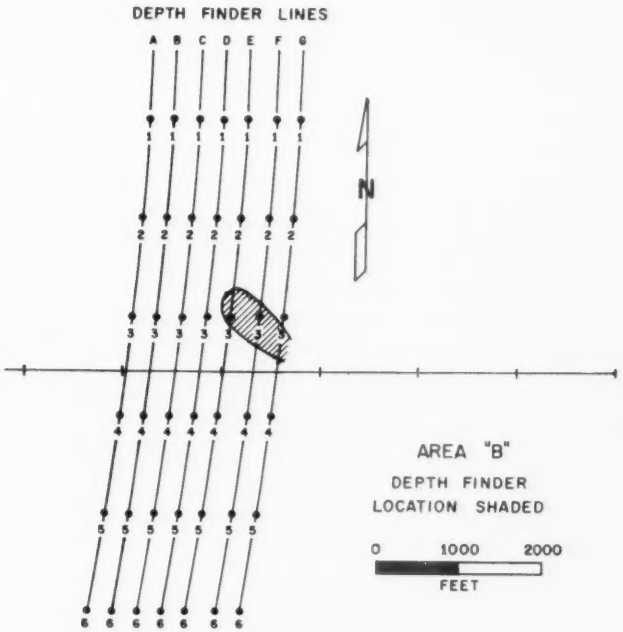

FIG. 9. Seismic and sonic depth finder lines in "*B*" area.

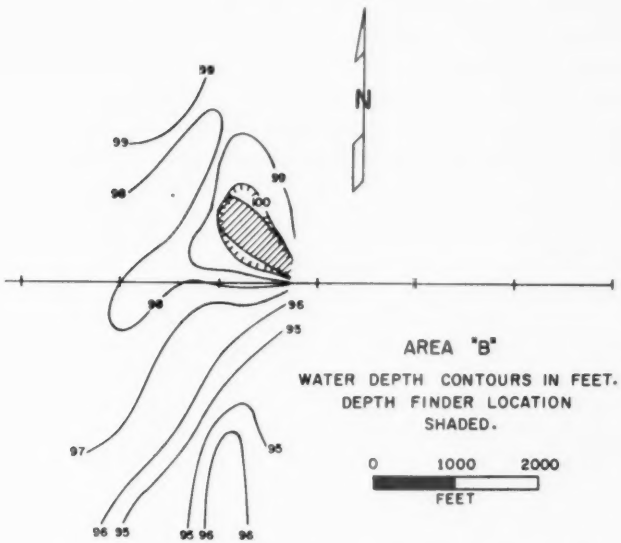

FIG. 10. Contour map of Gulf floor in "*B*" area derived from depth finder recordings.

much larger area with separations of 1,200 ft. Both grid patterns were centered over the reflecting source. Specific gravity measurements were made of near surface samples and near bottom samples. Surface temperatures were measured but bottom temperatures were not obtained because of failure of the temperature measuring apparatus. A total of 134 specific gravity measurements were made. A typical series of measurements averaged 72°F. for the temperature measurements and 36.3 parts per thousand for the salinity measurements. Under such conditions, the velocity of sound in sea water is approximately 5,005 ft/sec. The maximum difference of specific gravity observed for any series of measurements including surface and bottom measurements corresponds to a difference of salinity of only 5 parts per 1,000. Such a difference would result in a change in velocity of approximately 25 ft/sec. The maximum surface temperature difference for any series of measurements was 2 degrees Fahrenheit which corresponds to a change in velocity of approximately 10 ft/sec.

The variations in the salinity and temperature measurements are such that they give no evidence of any artesian water flow in the area, and the velocity discontinuities that might arise from these variations are considered to be too small to produce the reflections recorded.

CONCLUSIONS

In conclusion, it can be said that the nature of the reflecting sources is still not exactly known. The depth finder recordings can be interpreted to indicate mud or silt filled depressions which conceivably might form the reflecting areas. In any event, it must be concluded that in the general area there are a number of relatively small areas on or just below the Gulf floor which have the necessary acoustical properties to give rise to seismic reflections that can be recorded over considerable distances.

REFERENCE

Adams, K. T., 1942, Hydrographic Manual: Washington, U. S. Govt. Printing Office.

GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 765-770, 5 FIGS.

SOME UNUSUAL REFLECTIONS OF SOUND IN THE OCEAN*

RICHARD L. BURLING†

ABSTRACT

Occasionally, in routine seismic exploration for submarine structures, seismograms are obtained which show energy returned by something within the ocean. This effect is shown to result from relatively small, motile, gregarious objects, such as whales.

In routine seismic exploration of submarine geologic structures by the reflection method, it is usual to detonate an explosive a few feet below the ocean surface, and detect the reflected energy by means of an *L*-shaped array of detectors also a few feet below the surface. The first arrival of energy is normally that which has traveled directly from the shot to the detector through water; except that in quite shallow water, energy that is critically refracted so as to travel approximately horizontally through the rock near the ocean bottom, may arrive first. Again except in very shallow water, the arrival of the ocean bottom reflection is usually quite distinct from the direct arrival. In surveying the continental shelf off the coast of Santa Barbara and Ventura Counties in southern California, many records have, however, been obtained in which there is also energy (other than the ocean bottom refraction) arriving between the direct water-borne wave from the shot and the ocean bottom reflection. Some of these arrivals, apparent only on the records from quite deep water, represent air-borne sound from the shot, since their arrival times are proportional to, and about five times as great as, those of the direct water-borne first breaks. Others have moveouts and "curvatures" exactly equal to those of the first breaks, so must represent bubble noise. There still remain, out of a total of the order of a thousand shots, 32 records on which the arrivals must have other explanations, and there has been some speculation as to their origin. They were obtained where ocean depths varied from 400 ft to 1,000 ft. Fig. 1 reproduces the two records showing the strongest arrivals; others vary down to the limit of bare detectability. No automatic volume control was used.

Certain characteristics of the arrivals enable one to reject some hypotheses as to their origin. The large moveout curvatures (usually even larger than those of the first breaks) preclude attributing these arrivals to any nearly-level nearly-plane reflector such as a hypothetical layer of marine organisms or discontinuity in the density of sea water. The facts that, while observed on only a small fraction of the records, these arrivals quite often appear to tie from one record to the next, that two or more distinctly different arrivals frequently appear on the same record, and that no such arrivals have been observed before the first breaks,

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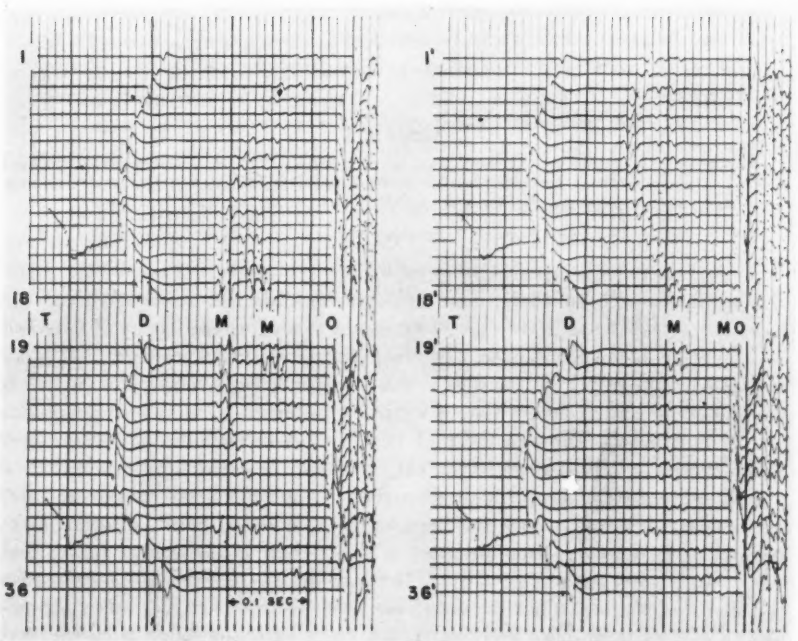

FIG. 1. Records showing arrival of energy (*M*) between that coming direct from shot to detectors (*D*) and that reflected from the ocean bottom (*O*). *T* indicates the detonation time. The positions of the detectors, identified by numbers to the left of the traces, are mapped in Fig. 5.

exclude explanations requiring a random accident such as the explosion of an odd can of powder, the backfiring of a boat motor, or a shot by another seismograph party.

If it can be assumed that the wave front for such an arrival is, at least to a first approximation, spherical (and this will include plane as a special case), then one can locate the center of this spherical wave front by using the observed move-outs and the known locations of the detectors. This center might in general be either a source of sound, a relatively small diffracting object scattering sound received from the shot, or a geometrical image of the shot point formed by some reflector, plane or curved. The computation locating this center is, unfortunately, very sensitive to the exact positions of the detectors, so cannot be carried out very accurately. In most cases the arrivals form a smooth curve on which one can find the position at which the energy first arrived, and to which there corresponds a "short-time" position on the cable along which the detectors are spaced. The center of the wave front should lie in a plane perpendicular to the cable at this short-time location. The center can be further restricted to a curved line locus in

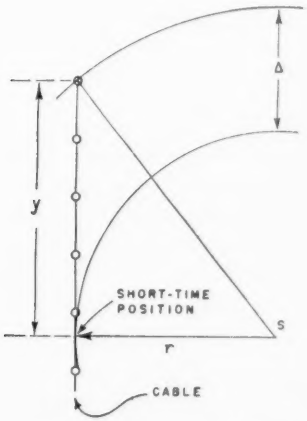

FIG. 2. The geometrical relationship leading to Equation (1) for the distance r between the center s of the wave front and the short-time position on a straight cable.

this plane by making use of the moveout representing the difference between the times of arrival at the short-time position and at the end of the cable. In the special case of a straight cable, this locus is a circle with its center at the short-time position, and a radius given by

$$r = \frac{y^2 - \Delta^2}{2\Delta} \tag{1}$$

where y is the distance between the short-time position and the end of the cable, and Δ is the moveout expressed in units of distance by multiplying the moveout time by the velocity of sound in water. See Fig. 2. In the more general case of a curved cable, the locus is an ellipse, being the intersection of the plane already mentioned with the two-sheet hyperboloid of revolution which is the locus of a point whose distance from two fixed points, the short-time position and the end of the cable, differ by a fixed amount, the moveout Δ. To find the location and shape of this ellipse, one can easily locate on it three points indicated in Fig. 3, where the r's are given by Equation (1) and the following:

$$r_1 = \frac{y_1^2 - (\Delta - \delta)^2}{2(\Delta - \delta)} \tag{2}$$

$$r_2 = \frac{y_1^2 - (\Delta + \delta)^2}{2(\Delta + \delta)} \tag{3}$$

If an arrival can be identified on both the line and cross cables, the intersection of the two planes through the short-time positions defines a vertical line on which the center of the wave front must lie. The intersections of this vertical line with

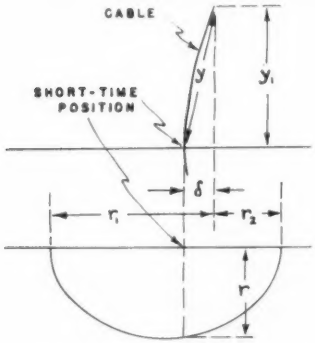

FIG. 3. Location of center of wave front for a curved cable. The upper part of the figure is a plan view of the cable. The lower part is a vertical plane through the short-time position, and shows the elliptic locus on which the center of the wave front must lie.

the elliptic loci in the two planes should be nearly coincident, and locate the center of the wave front.

Having located the center of our wave front, we can now use the observed time of the arrivals that we wish to interpret to distinguish among centers representing (1) a diffracting point, (2) a virtual image formed by a concave or convex reflector, and (3) a real image formed by a concave reflector, as illustrated in Fig. 4. We have case (1), (2), or (3), according to whether the actual observed arrival time is equal to, less than, or greater than, the time that would be required for a signal to go from the shot point to the center of the wave front and then to the detector. This same distinction can also be made independently, in cases

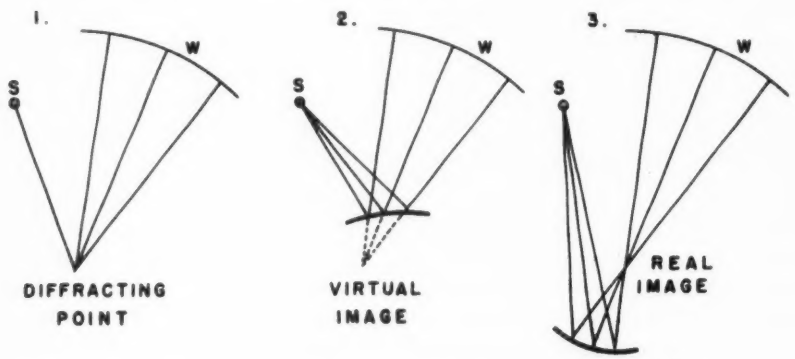

FIG. 4. Three different cases of reflection of sound from the same source *s*, giving rise to wave fronts *w* having the same shape and the same center.

in which there is a clear tie from one record to the next, by observing whether the center of the wave front determined from one record is in the same location (relative to a map of the ocean, not to the boats and cables) as that determined from the next record. We have case (1), (2), or (3) depending on whether the center of the wave front remains fixed, moves in the same general direction as the shot point, or moves in the opposite direction.

Centers have been determined, by the method outlined, for four cases in which it was fairly clear that one had corresponding line and cross cable arrivals. Three of these are from records shown in Fig. 1. The cable layouts are shown in Fig. 5. In all four cases, the arrival times agreed (to within about three milliseconds) with the interpretation of that center as a diffracting point rather

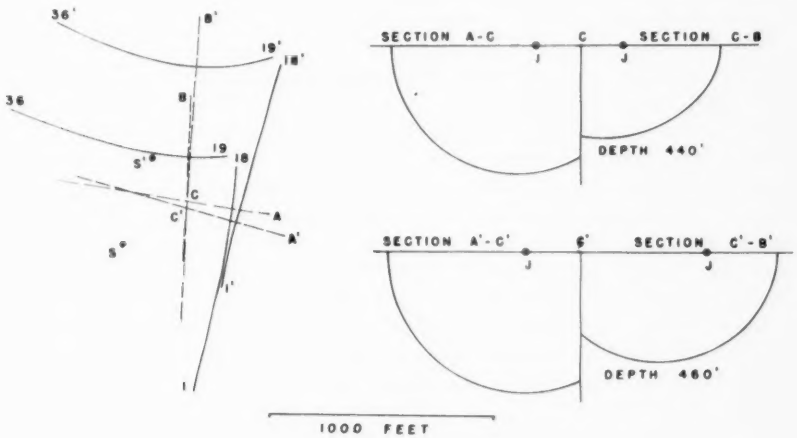

FIG. 5. The left portion of the figure is a plan showing relative locations of the shot points, s and s', and the detectors, numbered from 1 to 36 for each of the two shots used for the seismograms of Fig. 1. The right portion represents vertical planes with the elliptic loci on which the center of the wave front must lie; the cable crossing the section at J. The locations determined independently from the two shots coincide within experimental error.

that a reflected image. Two of these cases constituted a record-to-record tie, and determined center locations within fifty feet of each other (see Fig. 5); again favoring their interpretation as a diffracting point (i.e. a relatively small object). Two of the three locations determined were about 500 feet below the surface of the ocean, so that the interpretation of the diffracting points as being boats, or other objects floating on the surface, is not tenable. The ocean-bottom reflections (O) tie well, and indicate a reasonably smooth bottom at a depth of about 800 feet even precisely beneath the diffracting point. Thus the diffractors could not easily be objects resting on, or pinnacles projecting from, the bottom. It is difficult

to imagine an inanimate object that could remain suspended in stable equilibrium in water. It would have to have automatic control devices or the rather unlikely combination of a density equal to that of sea water with a compressibility even smaller than that of sea water. A sunken vessel, for example, would have to contain air in order to have the right density, but this air would give it a very large compressibility, so that its equilibrium would be unstable, and it would either rise to the surface or sink to the bottom. An object (such as a mine or submarine-net float) which was anchored, or trailed a chain or cable long enough to reach the bottom, would meet the requirements, possibly even that of being gregarious. But, considering also the fact that the arrivals often fail to tie from one record to the next, it would appear necessary to conclude that the diffractors are animate, i.e., that they are whales, large fish, small submarines, small compact schools of fish, or such.

Since some of the arrivals appear to result from small diffracting objects, one might tentatively experiment with the assumption that the rest of them are also to be interpreted in the same way. It is then possible, by using the observed time of arrival, to locate the diffracting center even in cases in which one does not have clearly correlated arrivals on both the line and cross cables. For three additional arrivals, locations were computed in this way, two of these three tied with arrivals on other records for which computed locations have already been mentioned. In each case, the location coincided within experimental error with that previously obtained. It would appear that, if the diffractors are motile, they do not mind our shooting—at least they often do not object strongly enough to swim away.

The author wishes to express his indebtedness to Mr. Calvin Kirby and Mr. Carl Savit of Western Geophysical Co. for their encouragement and suggestions, and to the Western Gulf Oil Company for permission to reproduce parts of their seismograms.

GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 771–779, 4 FIGS.

OBSERVATION OF THE VERTICAL GRADIENT OF GRAVITY IN THE FIELD*

STEPHEN THYSSEN-BORNEMISZA† AND W. F. STACKLER†

ABSTRACT

Field observations of the anomalous vertical gravity gradient were made at Houston, Texas, and over the Turner Valley structure near Calgary, Alberta, Canada. The results obtained are encouraging, but the precision of the measurements was to some extent reduced by vibrations generated in transporting the gravimeter up and down the tripod, as well as by gusts of wind.

INTRODUCTION

The main purpose of this paper is to present, probably for the first time, measurements of the vertical gravity gradient taken along a profile crossing a known geologic structure. The technique about to be described is still subject to serious limitations brought about by unfavorable atmospheric conditions.

It is possible today to calculate theoretically the vertical gradient of gravity from free air values of gravity observed over a surveyed area; and papers by Evjen (1936), Hofmann (1949), and Kosbahn (1949) give the necessary formulae. However, a function derived from another function cannot possibly introduce something really new. The derived function is bound to suffer from all the defects carried by the original function.

Conditions today are quite similar to those existing twenty-five years ago. At that time isogams were calculated and drawn from torsion balance values of the horizontal gravity gradient without recourse to actual measured values of gravity. Recently, however, high precision gravimeters have, to a large extent, superseded the older and more tedious procedures involved in the use of the torsion balance. The authors believe that observed values of the vertical gravity gradient could be used advantageously in order to improve present day gravity surveys.

EARLY EXPERIMENTAL EFFORTS

It has been known for some time that it is possible to determine the vertical gradient of gravity from observations of gravity with the gravimeter at two points, one above the other, at a known difference in elevation. Studies of this type have been made in the past making use of high buildings and vertical shafts. The early gravimeter did not have sufficient accuracy to produce satisfactory determinations of the vertical gravity gradient, and observations in buildings or shafts at that time were carried out principally for obtaining a calibration of the gravimeter (Schleusener, 1935).

* Manuscript received by the Editor December 1, 1955.

† Independent geophysicists in Cuba and Canada.

The first practical vertical gravity gradient observations were published by Hammer (1938) making use of large vertical elevation differences in high buildings.[1] Later, Thyssen-Bornemisza (1944) presented vertical gravity gradient observations utilizing quite small elevation differences ranging from one to five feet. The intent of the latter author at that time was gradually to increase the elevation difference to an amount suitable for practical field work. This result could not be achieved, although movable tripods and towers were utilized in later experiments. Vibrations set up in moving the gravimeter up and down, and by gusts of wind, prevented a satisfactory precision.[2]

Results of a more recent experiment carried out by Houston Technical Laboratories, making use of a light-weight Worden gravimeter and a 12 foot tripod, are shown in Fig. 1. The value obtained for the vertical gravity gradient, making use of all the readings, was 3062.8 ± 37.1 Eötvös units[3] and omitting the disturbed first reading, 3074.2 ± 4.1 Eötvös units. The total time required to make these observations and to obtain this single-station value of the vertical gravity gradient was one and one-half hours.

EXPERIMENTAL FIELDWORK

Following these early attempts at measurement of the vertical gravity gradient the present senior author carried out some more extended field experiments of the type just described. For this purpose Gravimeter Party No. 3 of the Jensen Surveys Ltd., Calgary, Alberta, Canada, was used. This party was equipped with a Worden gravimeter[4] and cooperated closely with Dr. W. F. Stackler in the field.

It was soon learned that the observer should not touch the gravimeter and tripod in making the observations. Therefore, the observer was supplied with an independent platform or ladder as shown in Fig. 2 upon which to stand while taking readings. The tripod bearing the instrument provided an elevation difference of 12.542 feet.

It was necessary to develop an improved technique in order to speed up the readings, and the moving of the gravimeter up and down the tripod. Advantages had to be taken of the relatively calm period between gusts of wind and it was necessary to keep the instrument drift under control. After some experience the average observation time of one regular set-up was reduced to from ten to fifteen minutes covering the series of observations at "down-up-down-up-down." Every single "down" or "up" consisted of four separate readings. The drift correction generally could be neglected because of the short time interval between two

[1] Consult Table III.

[2] In order to reduce vibrations it has been suggested by Thyssen-Bornemisza (paper presented at the 34th Annual Meeting Section Geodesy of the A.G.U., Transactions 1953, p. 323) to make use of a special swing system for moving the gravimeter up and down.

[3] 1 Eötvös unit $= 1 \times 10^{-9}$ c.g.s.

[4] Worden instrument No. W 129 with scale constant 0.09607 mg/division.

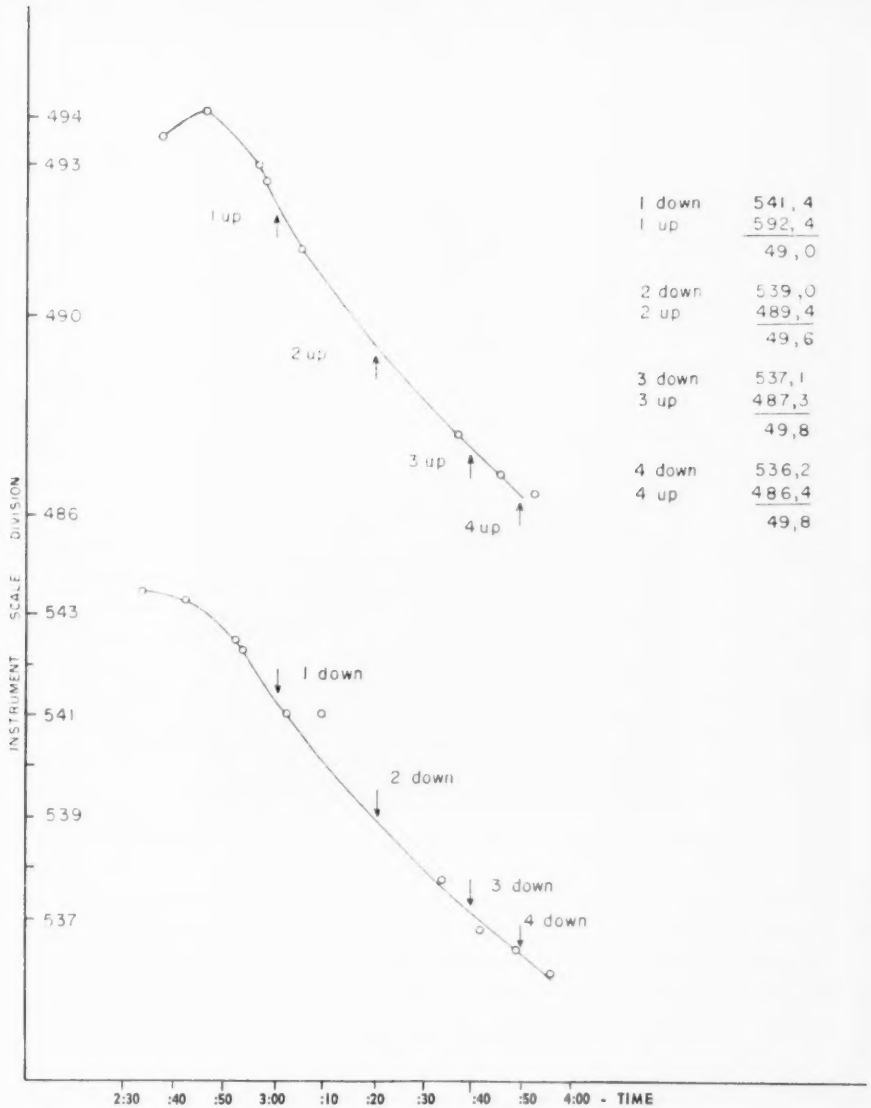

FIG. 1. Measurements of vertical gravity gradient of Houston Technical Laboratories. Meter constant = 0.021098 mg/division. Elevation difference = 11.198 feet.

FIG. 2. Observing the vertical gradient of gravity. Elevation difference =12.542 feet.

"down" or two "up" observations, equal to about five minutes. As a general rule, observations had to be discontinued with wind conditions turning unfavorable. This was the case when the frequency of wind gusts increased beyond a certain point.

THE GRADIENT PROFILE OVER THE TURNER VALLEY STRUCTURE

The Turner Valley structure near Calgary provided a suitable formation over which to run an experimental profile. Previous gravimeter surveys (Stackler 1954, 1955) and the geology of that area suggested relatively large fluctations of the anomalous vertical gradient of gravity.

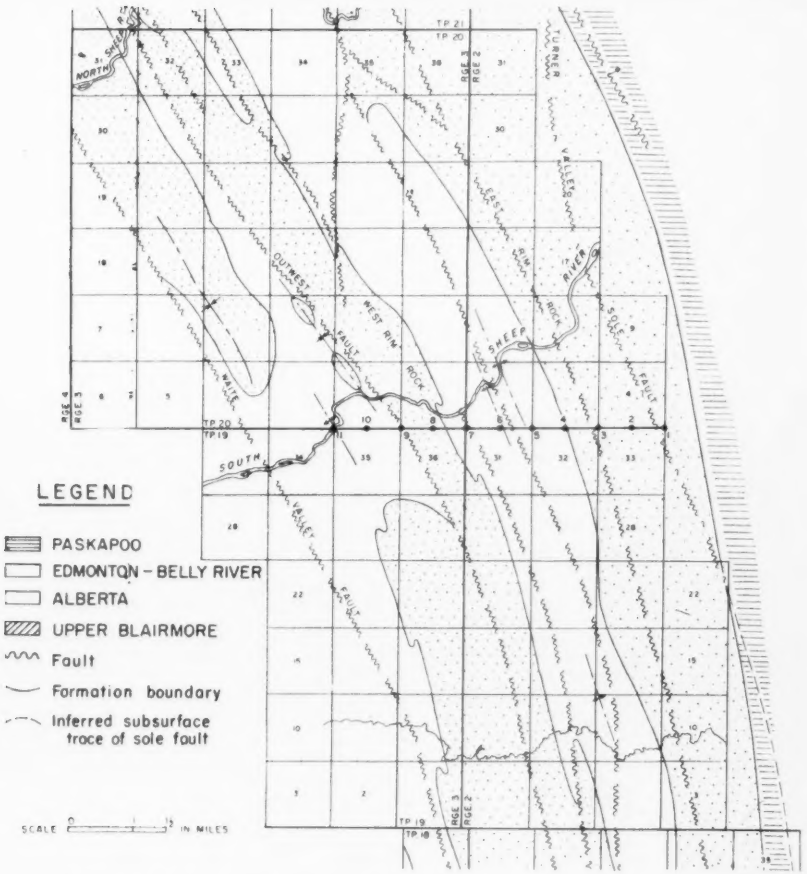

FIG. 3. Station locations in Turner Valley field for observed vertical gravity gradient.

Fig. 3 shows the layout of stations. Eleven separate stations were occupied with the interval of one half mile between stations. Observed quantities are given in Table I and the cross section of the vertical gradient profile is shown in Fig. 4. It will be seen that the precision over the whole profile is 10.1 Eötvös units. Table II gives the bulk density of the various geologic formations encountered in the area. These values were obtained from 267 separate density determinations.

These studies just described were carried out during the latter part of July, 1955 so as to take advantage of good weather conditions.

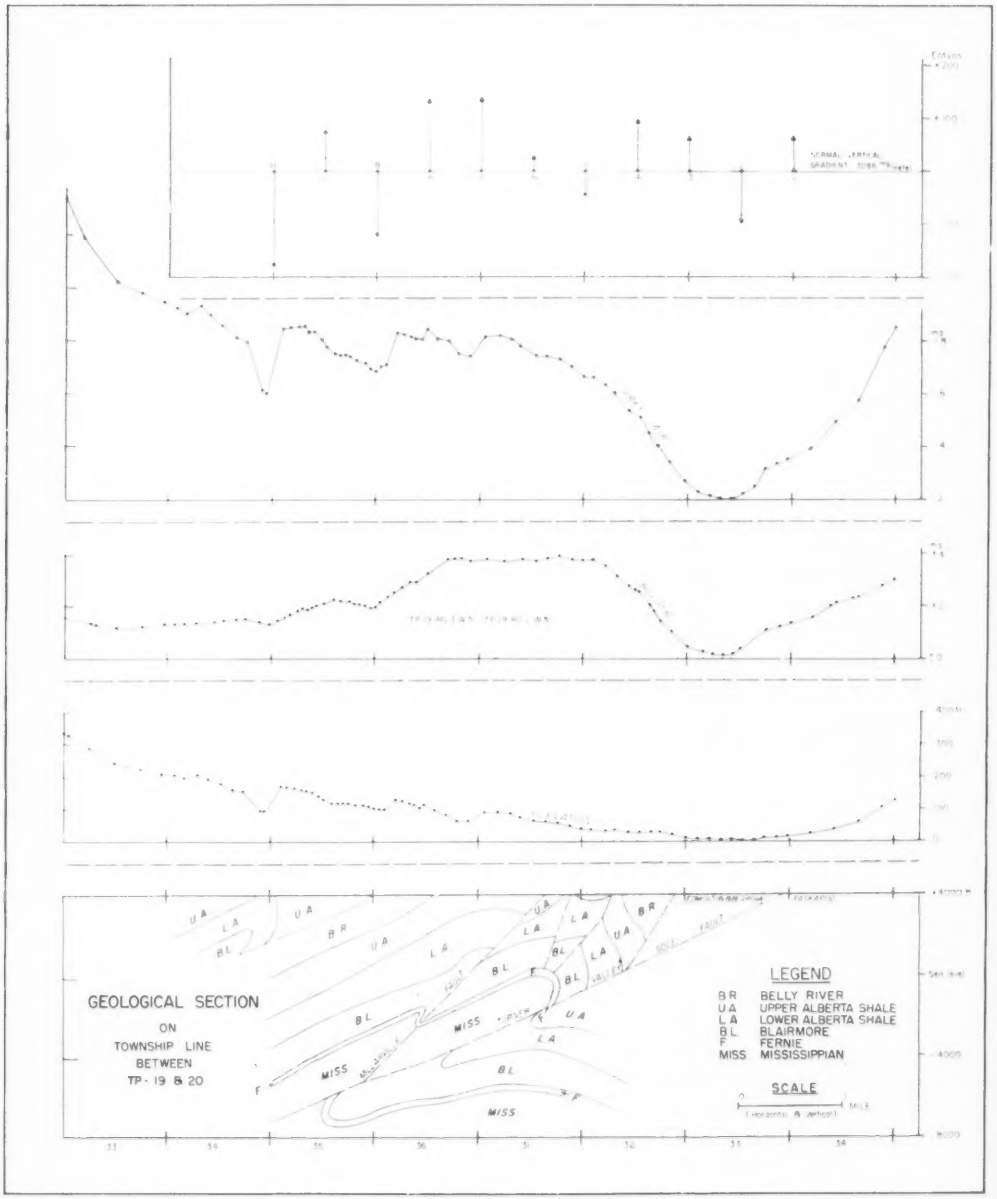

FIG. 4. Results of gravity intensity and observed vertical gradients in Turner Valley field.

TABLE I

ELEVEN OBSERVED STATIONS ON TURNER VALLEY STRUCTURE

Location	Observed g between "up" and "down" in Single 0.01 mg	Average 0.01 mg	Elevation Range in Feet	Vertical Gradient in Eötvös	Vertical Grad.—Normal in Eötvös	Departure from Normal in Percent
1 N.E. Corner Sec. 33	119.99 120.09 118.84 119.22 120.76 121.72 121.05 121.53	120.40	12.542	3,149.6± 9.7	+ 64	2.07±0.31
2 N.C. Line Sec. 33	114.80 114.52 114.71 112.79 113.94 114.52 115.38	114.38	12.542	2,992.1± 8.1	− 94	3.05±0.25
3 N.E. Corner Sec. 32	121.32 120.49 119.55	120.45	12.542	3,150.9±13.4	+ 65	2.11±0.43
4 N.C. Line Sec. 32	121.32 121.53 122.16	121.67	12.542	3,182.8± 6.6	+ 97	3.14±0.21
5 N.E. Corner Sec. 31	115.76 116.34 117.49 117.49 116.92 115.87 115.87 115.48 115.09 114.52	116.08	12.542	3,036.6± 8.1	− 49	1.59±0.26
6 N.C. Line Sec. 31	117.99 118.09 120.70	118.93	12.542	3,111.2±23.2	+ 26	0.81±0.75
7 N.E. Corner Sec. 36	123.31 123.30 122.78	123.13	12.542	3,221.0± 4.6	+135	4.37±0.15
8 N.C. Line Sec. 36	123.30 122.58 123.20	123.03	12.542	3,218.4± 5.9	+133	4.28±0.19
9 N.E. Corner Sec. 35	111.52 113.19 115.27	113.33	12.542	2,964.7±28.4	−121	3.92±0.92
10 N.C. Line Sec. 35	120.80 120.80 120.80	120.80	12.542	3,160.1± 0	+ 74	2.40±0.0
11 N.E. Corner Sec. 34	107.45 107.03 107.45	107.31	12.542	2,807.2± 3.7	−178	5.80±0.12

TABLE II
DENSITY VALUES IN TURNER VALLEY AREA

Formation	Type	Relative Thickness in Feet	Bulk Density
Tertiary Paskapoo	Fresh Water, ss+shale	2,700	2.36
Cretaceous Edmonton	Fresh Water, ss+shale	2,600	2.47
Cretaceous Bearpaw	Marine, ss+shale	600	2.35
Cretaceous Belly River	Fresh Water sandstone	4,600	2.46
Cretaceous Upper Alberta Shale	Fresh Water sandstone		2.52
Cretaceous Lower Alberta Shale	Marine, ss+shale		2.39
Cretaceous Kootenay & Blairmore	Fresh Water, ss+shale with coal seams	1,600	2.56
Jurassic Fernie			
Mississippian	Marine	2,600	2.62 2.56

CONCLUSIONS

We believe that we have shown by experiment that it is possible to make practical vertical gravity gradient measurements in the field through the use of a sensitive gravimeter when proper care is taken. It has been pointed out that gusts of wind may interfere with the field observations and that observations should be undertaken during periods of good weather.‡ Theoretical and practical implications resulting from these observations cannot at present be appraised completely and more experiments are obviously necessary before a final judgment of the practicability of the procedure can be made.

TABLE III
EXPERIMENTAL VALUES OF VERTICAL GRADIENT OF GRAVITY

Experimenters	Year	Elevation Range in Feet	Observed Vertical Gradient, mg/meter	Deviation from Normal Value in Percent
Jolly	1881	68.913	−0.295	−4½
M. Thiesen	1890	37.660	−0.303	−2
Scheel+Diesselhorst	1895	97.541	−0.289	−6½
Richarz+Kriegar-Menzel	1898	7.424	−0.285	−7½
Values obtained with Gravimeters				
S. Hammer Empire State Bld., New York	1938	953.4	−0.3128 ±0.0003	+1.4
St. Thyssen-Bornemisza	1943	1.64	−0.310* ±0.006	+0.5
Houston Techn. Laboratories out-door observation	1953	11.198	−0.3063 ±0.0037	−0.8
Thyssen-Bornemisza+Stackler (fieldwork by Jensen Surveys Ltd)	1955	12.542	−0.3096† ±0.0010	+0.33

* See footnotes pp. 38, 40, of the paper: Thyssen-Bornemisza, St., 1944.

† Average value obtained from observations at eleven different localities over Turney Valley structure in Alberta, Canada. Compare Table I for details.

‡ Vertical gradient observations, if carried out under water, should be less disturbed by this kind of interference.

Attention is called to the comparison of the vertical gradient profile with the isopach residual profiles calculated and plotted by Stackler (1955) in his paper. The comparison may suggest that, in the case where the datum plane of a survey is close to the surface, observed vertical gradient values could be used for improving on the *free air* correction and on the gravimetric presentation of the *surface geology*.

At the end of this paper there is given in Table III the gradual improvement in vertical gravity observations during the course of this development. Some historical measurements also are included.

ACKNOWLEDGMENT

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POTENTIAL AND APPARENT RESISTIVITY OVER DIPPING BEDS*

JEROME CHASTENET DE GERY† AND GEZA KUNETZ†

ABSTRACT

The potential field due to a point source of current, located on the surface of the earth near a dipping bed, is given in an exact expression and modified expressions are developed for computations. These expressions lead to graphs of the potential field and to apparent resistivity vertical profiles which are presented. The Schlumberger electrode configuration is used. This configuration consists of two current electrodes and two potential electrodes, the latter placed close enough together that the current density between them can be considered to be uniform. With this configuration oriented perpendicular to the strike of the dipping bed, the apparent resistivity is paradoxical in that it approaches either zero or infinity as the electrode separation increases without limit.

INTRODUCTION

In a recent paper, Maeda (1955) presented a complete solution to the dipping bed problem in electrical prospecting. Van Nostrand and Cook (1955) followed that paper with a critical review of the literature treating the problem, emphasizing in particular the limitations of the so-called "image method." Previously, Chastenet de Géry and Kunetz at the E.A.E.G. meeting in Milan had also protested against the misuses of the image method and had given an exact theoretical solution for arbitrary dips and resistivity contrast, together with several numerical examples and practical charts. Huber (1955) offered an alternate complete solution based upon the analogous electrostatic solution given by Rice (1940). In his paper, Huber presented both vertical and horizontal profiles for the Wenner configuration oriented perpendicular to the strike of the dipping beds. Earlier, Sŭmi (1953) had given an exact method of determining dip by the simple device of expanding the Wenner configuration along the outcrop of the dipping contact between two beds. An exact solution for this case can be obtained from elementary considerations. He included charts to implement his method.

Previous to this group of papers, the only complete solution to the general problem of dipping beds with arbitrary resistivity contrast was published in Russian by Skalskaya (1948). It is the purpose of this note to present the high lights of the oral paper mentioned above, especially as it supplements the critical review of Van Nostrand and Cook. We also want to give in more detail the computational forms of the solution as first derived by Skalskaya and to present additional examples of the application of these solutions. At the same time, we want

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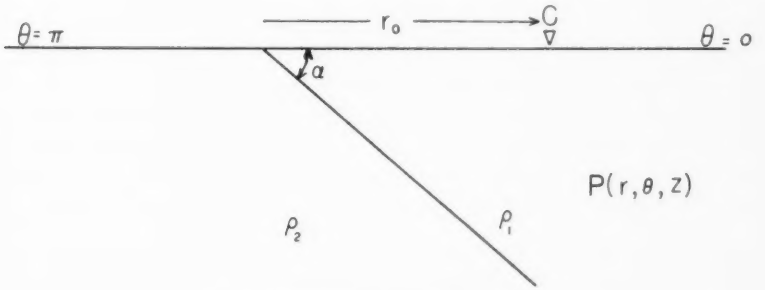

FIG. 1. Cross-section showing dipping bed.

to describe the Schlumberger configuration which seems to have escaped the notice of most American workers. In this paper, we shall use the notations adopted in the two above-mentioned papers from *Geophysics*.

The basic problem is to determine the electric potential due to a point source of current in the vicinity of a dipping contact between beds of different resistivities (Fig. 1). We adopt a cylindrical coordinate system with the z-axis along the intersection of the dipping contact and the earth's surface; the origin is such that $z=0$ for the point source; the angle θ is such that $\theta=0$ for the earth's surface to the right of the origin and $\theta=\pi$ to the left. In cylindrical coordinates, Laplace's equation is

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial V}{\partial r}\right]+\frac{1}{r^2}\frac{\partial^2 V}{\partial \theta^2}+\frac{\partial^2 V}{\partial z^2}=0. \tag{1}$$

The general solution of this equation has three simple forms which correspond to the three types of boundary conditions. These forms are exemplified by the three expansions of the reciprocal distance which were originally derived by Dougall (Gray et al., 1931, p. 102–103). Where R is the distance between the points $(P_0(r, 0, 0)$ and $P(r, \theta, z)$, these expansions are

$$\begin{aligned}\frac{1}{R} &= \int_0^\infty e^{-\lambda z}J_0(\lambda\sqrt{r_0^2+r^2-2r_0 r\cos\theta})d\lambda \\ &= \sum_{m=0}^{\infty}(2-\delta_{0m})\cos m\theta\int_0^\infty e^{-\lambda z}J_m(\lambda r_0)J_m(\lambda r)d\lambda\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{1}{R} &= \frac{2}{\pi}\int_0^\infty \cos\lambda z K_0(\lambda\sqrt{r_0^2+r^2-2r_0 r\cos\theta})d\lambda \\ &= \frac{2}{\pi}\sum_{m=0}^{\infty}(2-\delta_{0m})\cos m\theta\int_0^\infty \cos\lambda z I_m(\lambda r_0)K_m(\lambda r)d\lambda\end{aligned} \tag{3}$$

$$\frac{1}{R} = \frac{4}{\pi^2}\int_0^\infty \cos \lambda z d\lambda \int_0^\infty \cos ht(\pi - \theta) K_{it}(\lambda r_0) K_{it}(\lambda r) dt. \tag{4}$$

The Bessel functions are used as defined by Gray et al. (1931); $J_n(z)$ is the ordinary Bessel function, $I_n(z)$ is the modified Bessel function of the first kind, and $K_n(z)$ is the modified Bessel function of the second kind. It is stipulated that $z>0$ in equation 2, $r>r_0$ in equation 3, and $0<\theta<2\pi$ in equation 4. The symbol δ_{0n} is the kronecker delta which equals zero when $m\neq 0$ and unity when $m=0$.

These are the three forms for which Maeda expressed the hope that they would lead to different solutions of appropriate regions of convergence. However, only the latter form (equation 4) can be used for the present problem. The first form (equation 1) is applicable to horizontally layered beds (Stefanesco et al., 1930) and the second form is useful in well logging problems (Fok, 1933).

As shown also by both Maeda and Skalskaya, the most general solution to the problem is given by

$$\begin{aligned} V_1 &= \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{4}{\pi^2}\int_0^\infty \cos \lambda z d\lambda \int_0^\infty A(t) \cosh t\theta K_{it}(\lambda r_0) K_{it}(\lambda r) dt \right. \\ V_2 &= \frac{I\rho_1}{2\pi}\left(\frac{4}{\pi^2}\right)\int_0^\infty \cos \lambda z d\lambda \int_0^\infty B(t) \cosh t(\pi - \theta) K_{it}(\lambda r_0) K_{it}(\lambda r) dt \end{aligned} \tag{5}$$

where V_1 applies in the first medium, which contains the current electrode, and V_2 in the second medium. The parts of the integrands, as yet unspecified, are

$$\begin{aligned} A(t) &= \frac{k \sinh 2t(\pi - \alpha)}{\sinh t\pi - k \sinh t(\pi - 2\alpha)} \\ B(t) &= \frac{(1 + k) \sinh t\pi}{\sinh t\pi - k \sinh t(\pi - 2\alpha)} \end{aligned} \tag{6}$$

where

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}.$$

We now require an integral representation of the product of two modified Bessel functions. This representation can be derived directly by starting with Schlafli's (Watson, 1945, p. 181) integral representation, which can be transformed as follows:

$$K_\nu(z) = \int_0^\infty e^{-z \cosh t} \cosh \nu t dt = \frac{1}{2}\int_{-\infty}^\infty e^{-z \cosh t - \nu t} dt \tag{7}$$

and is valid for $|\arg z| < \pi/2$. Therefore, we can write

$$K_{it}(\lambda r_0) K_{it}(\lambda r) = \frac{1}{4}\int_{-\infty}^\infty \int_{-\infty}^\infty e^{-\lambda r_0 \cosh u - \lambda r \cosh v - it(u-v)} du dv. \tag{8}$$

If we change variables by letting $u+v=s$ and $u-v=2V$, the integral becomes

$$\frac{1}{4}\int_{-\infty}^\infty e^{-its} ds \int_{-\infty}^\infty e^{-\lambda[r_0 \cosh((s/2)+V) + r \cosh((s/2)-V)]} dV. \tag{9}$$

The inner integral may also be manipulated into the form,

$$\int_{-\infty}^{\infty} e^{-\lambda p \cosh (V+\phi)} dV \tag{10}$$

where $P^2 = r_0^2 + r^2 + 2r_0 r \cosh s$ and

$$\phi = \tanh^{-1}\left(\frac{r_0 - r}{r_0 + r} \tanh s/2\right).$$

From the definition of equation 7, we see that this integral is $2K_0(\lambda p)$ so that we finally get

$$K_{it}(\lambda r_0) K_{it}(\lambda r) = \int_0^{\infty} \cos t s K_0(\lambda \sqrt{r_0^2 + r^2 + 2r_0 r \cosh s}) ds. \tag{11}$$

We combine this integral representation of the product with equation 3 above in order to express the potential functions of equations 5 in terms only of elementary circular and hyperbolic functions:

$$\begin{aligned} V_1 &= \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{2}{\pi}\int_0^{\infty} A(t) \cosh t\theta dt \int_0^{\infty} \frac{\cos tsds}{\sqrt{z^2 + r_0^2 + r^2 + 2r_0 r \cosh s}}\right\} \\ V_2 &= \frac{I\rho_1}{2\pi}\left(\frac{2}{\pi}\right)\int_0^{\infty} B(t) \cosh t(\pi - \theta) dt \int_0^{\infty} \frac{\cos tsds}{\sqrt{z^2 + r_0^2 + r^2 + 2r_0 r \cosh s}}. \end{aligned} \tag{12}$$

We have separated $A(t)$ and $B(t)$ from the rest of the above integrands because these are the parts which are manipulated in order to simplify computations for special cases. The second expression is the simpler of the two and we consider it first. If we perform one step of division, it can be shown that

$$B(t) = (1 + k) + \frac{k(1 + k) \sinh t(\pi - 2\alpha)}{\sinh t\pi - k \sinh t(\pi - 2\alpha)}. \tag{13}$$

When the first term on the right side of equation 13 is placed back in equation 5, it is easily seen by comparison with equation 4 that the resulting term leads to a term which corresponds to the only permissible image; in this case, it is the same as the image which would exist if the boundary were vertical. The second term in equation 13 leads to a correction to the image solution. We have then

$$\begin{aligned} V_2 = \frac{I\rho_1}{2\pi}\Bigg\{&\frac{1 + k}{R} + \frac{2k}{\pi}(1 + k)\int_0^{\infty} \frac{\sinh t(\pi - 2\alpha) \cosh t(\pi - \theta)}{\sinh t\pi - k \sinh (\pi - 2\alpha)} dt \\ &\cdot \int_0^{\infty} \frac{\cos tsds}{\sqrt{z^2 + r_0^2 + r^2 + 2r_0 r \cosh s}}\Bigg\}. \end{aligned} \tag{14}$$

This expression holds for all values of α between 0 and π and is useful when the current electrode is not in the same medium as the potential electrode.

In the case of $A(t)$, we must consider three separate cases which are distinguished by the values of α. If α lies between $\pi/2$ and π, $A(t)$ retains the value given above. Therefore, in this range of α,

$$V_1 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{2k}{\pi}\int_0^\infty \frac{\sinh 2t(\pi-\alpha)\cosh t\theta}{\sinh t\pi - k\sinh t(\pi-2\alpha)}\,dt \cdot \int_0^\infty \frac{\cos tsds}{\sqrt{z^2+r_0^2+r^2+2r_0r\cosh s}}\right\}. \tag{15}$$

If α lies between 0 and $\pi/2$, $A(t)$ may be separated into two parts:

$$A(t) = \sum_{n=1}^{N} 2k^n \cosh t(\pi - 2n\alpha) - \frac{(1-k^2)\sum_{n=1}^{N-1} k^n \sinh 2n\alpha t + k^N \sinh 2N\alpha t - k^{N+1}\sinh\left[2\pi - 2(N+1)\alpha\right]t}{\sinh t\pi - k\sinh t(\pi-2\alpha)} \tag{16}$$

where N is the integer lying between $\pi/2\alpha$ and $(\pi/2\alpha)-1$. As in the previous case, the first part of $A(t)$ can be related to images. In this case, the images are the first N images of the set which are obtained by successive reflections in the dipping contact together with the corresponding reflections in the earth's surface. The remaining part constitutes a correction to the image solution. Therefore, when $0<\alpha<\pi/2$ we have

$$V_1 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + 2\sum_{n=1}^{N}\frac{k^n}{\sqrt{z^2+r_0^2+r^2-2r_0r\cos 2n\alpha}} - \frac{2}{\pi}(1-k^2)\int_0^\infty \frac{\sum_{n=1}^{N-1} k^n \sinh 2n\alpha t + k^N \sinh 2N\alpha t - k^{n-1}\sinh\left[2\pi - 2(N+1)\alpha\right]t}{\sinh t\pi - k\sinh t(\pi-2\alpha)} \cdot \cosh t\theta dt \cdots \times \int_0^\infty \frac{\cos tsds}{\sqrt{z^2+r_0^2+r^2+2r_0r\cosh s}}\right\}. \tag{17}$$

This equation is useful for arbitrary angle of dip when the current electrode is on the down-dip side of the outcrop of the dipping contact.

In the special case when α is the Nth submultiple of $\pi/2(\alpha=\pi/2N)$, the Nth image falls on the earth's surface where $\theta=\pi$ and equation 13 is reduced to

$$V_1 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{k^N}{\sqrt{z^2+(r_0+r)^2}} + 2\sum_{n=1}^{N-1}\frac{k^n}{\sqrt{z^2+r_0^2+r^2-2r_0r\cos 2n\alpha}} - \frac{2}{\pi}(1-k^2)\int_0^\infty \frac{\sum_{n=1}^{N-1} k^n \sinh 2n\alpha t\cosh t\theta}{\sinh t\pi - k\sinh t(\pi-2\alpha)}\,dt \cdot \int_0^\infty \frac{\cos tsds}{\sqrt{z^2+r_0^2+r^2+2r_0r\cosh s}}\right\}. \tag{18}$$

We have shown that each of the above potential functions consists of an image solution plus a "correction" term. Whenever the image theory is adequate to solve the dipping bed problem, the correction term will vanish. For example, the correction term in equation 18 vanishes whenever $K = \pm 1$. Therefore we are led to the conclusion, previously drawn by other workers, that image theory is valid for the dipping bed problem when the lower bed is either perfectly conducting or perfectly insulating and when the angle of dip is a sub multiple of $\pi/2$ and, even then, only in the upper bed.

These correction terms can be reduced to simple integrals containing only elementary functions through the use of Mittag-Lefflers series or special cases thereof. In the case of equation 18, there will be a finite number of such integrals; but, in the case of equation 13, there will be an infinite series of integrals. For example, let $\alpha = \pi/4$ for which case equation 14 is applicable and is written as

$$V_1 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{k^2}{\sqrt{z^2 + (r_0 + r)^2}} + \frac{2k}{\sqrt{z^2 + r_0^2 + r^2}}\right.$$

$$- \frac{2k}{\pi}(1 - k^2)\int_0^\infty \frac{\sinh \frac{\pi t}{2}}{\sinh \pi t - k \sinh \frac{\pi t}{2}} dt \qquad (19)$$

$$\left. \cdot \int_0^\infty \frac{\cos ts ds}{\sqrt{z^2 + r_0^2 + r^2 + 2r_0 r \cosh s}}\right\}$$

on the earth's surface where $\theta = 0$. We divide both the numerator and denominator of the integrand by $\sinh (\pi t/2)$ so that it becomes

$$\frac{1}{2 \cosh \pi t/2 - k}.$$

Letting $k = -2 \cos \delta$, the integrand becomes

$$\frac{1}{2 \cosh \pi t/2 + 2 \cos \delta}.$$

We first perform the integration with respect to t, whence we get

$$\int_0^\infty \frac{\cos ts ds}{2 \cosh \pi t/2 + 2 \cos \delta} = \frac{\sinh 2s\delta/\pi}{\sin \delta \sinh 2s}. \qquad (20)$$

Then we change the remaining variable of integration by letting $(2s/\pi) \rightarrow s$ in order to make these results identical to those given by Van Nostrand and Cook. The above steps finally lead to the following expression for the potential:

$$V_1 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{k^2}{\sqrt{z^2 + (r_0 + r)^2}} + \frac{2k}{\sqrt{z^2 + r_0^2 + r^2}} - \frac{k(1 - k^2)}{\sin\delta}\int_0^\infty \frac{\sinh \delta s ds}{\sinh \pi s\sqrt{z^2 + r_0^2 + r^2 + 2r_0 r\cosh \pi s/2}}\right\}. \tag{21}$$

Skalskaya made use of the same expansions we have used. However, she carried out the integration in a different order and made use of special integrals involving modified Bessel functions. It can be shown in a similar fashion that the potential function on the other side of the dipping contact is

$$V_2 = \frac{I\rho_1}{2\pi}\left\{\frac{1 + k}{\sqrt{z^2 + (r_0 + r)^2}} + \frac{k(1 + k)}{\sin\delta}\int_0^\infty \frac{\sinh \delta s ds}{\sinh \pi s\sqrt{z^2 + r_0^2 + r^2 + 2r_0\cosh \pi s/2}}\right\}. \tag{22}$$

The integral appearing in V_1 and V_2 is easily evaluated by numerical methods. In order to work on both sides of the dipping contact, it is customary to use a complementary pair of solutions applicable when $\alpha = 135°$. These solutions represent potentials when the current electrode is on the up-dip side of the outcrop of the dipping contact.

The Compagnie Générale de Géophysique has worked out both formulae and curves for values of N up to 12, which corresponds to a dip of 15°. For smaller angles of dip, satisfactory approximate methods have been worked out. As an example, we will show the numerical results for the angle of dip equal to 45°.

THE SCHLUMBERGER ELECTRODE CONFIGURATION

The Schlumberger electrode configuration consists of two current electrodes, A and B, and two potential electrodes, M and N (Fig. 2). The line between the current electrodes forms the base of the system and the data are generally expressed in terms of one-half the distance between these electrodes. The potential electrodes are kept close enough together that the electric field between them can be considered to be constant. In the computation of the apparent resistivities from field measurements, the exact relative locations of the four electrodes are taken into account. The formula used for the apparent resistivity is

$$\rho_a = K\frac{\Delta V}{I} \tag{23}$$

where I is the current flowing in the earth, ΔV is the potential difference between the potential electrodes, and the geometrical factor is

$$K = \frac{2\pi}{\left(\frac{1}{AM} - \frac{1}{AN}\right) - \left(\frac{1}{BM} - \frac{1}{BN}\right)}. \tag{24}$$

In field use of the Schlumberger configuration of electrodes, the potential electrodes are moved only once out of every four or five changes of the power electrodes. Thus, for the five or six different values of $\overline{AB}$ in the interval from 100 to 800 meters, $\overline{MN}$ would have the fixed value of about 20 meters. In the following interval for $\overline{AB}$ up to 4,000 meters, $\overline{MN}$ would have the fixed value of about 100 meters. Usually, both values of $\overline{MN}$ are used for some readings in the transition from one interval to the next.

The principal advantage in this technique is that the influence of local inhomogeneities close to the potential electrodes can be clearly located on the apparent resistivity curves. These effects are shown by the differences between the results obtained with the same $\overline{AB}$ and different $\overline{MN}$'s. On the other hand, these

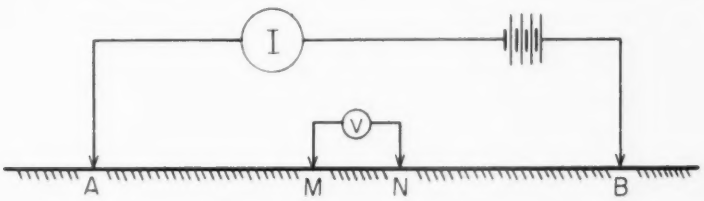

FIG. 2. Schematic diagram of Schlumberger configuration.

local heterogeneities do not appreciably alter the shape of those arcs of the resistivity curves which have been obtained with a given $\overline{MN}$; they only displace the arcs as whole units. This fact often allows one to make a correction and to trace the diagram which would have been obtained in a laterally homogeneous earth.

A schematic representation of this idea is shown in Fig. 3. The upper curve contains three segments, each of which represents data taken with one of three different values of $\overline{MN}$. Since a local inhomogeneity existed near one or both of the potential electrodes when $\overline{MN}$ had the second value used, segment B of the curve is displaced upward from the other two. Obviously, it is easy to connect segments A and C correctly by moving segment B downward to its correct position. The lower curve illustrates, for example, what might have been obtained with the Wenner configuration as it is normally used. The effect of the local inhomogeneity can not be differentiated from the effects from deep horizontal discontinuities on the smooth Wenner curve.

In order to construct theoretical curves for the Schlumberger configuration, the apparent resistivity is computed from the electric field which is calculated midway between the two current electrodes. The appropriate equation for the apparent resistivity is:

$$\rho_a = \pi L^2 \frac{E}{I} \tag{25}$$

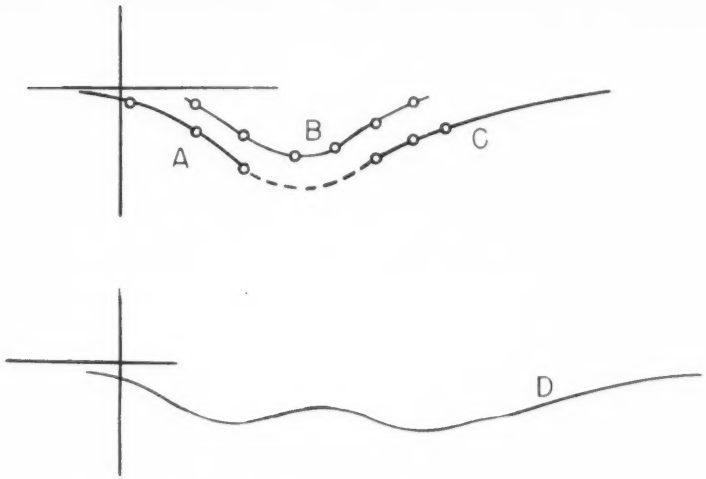

FIG. 3. Qualitative effect of inhomogeneity on resistivity curves. *A*, *B*, and *C* are segments of the Schlumberger curve; *D* is the Wenner curve.

where E is the magnitude of the component of the gradient along the line of electrodes. In order to obtain comparable data in the field, the potential electrodes would have to be infinitely close together. Discrepancies, arising from the fact that the actual distance $\overline{MN}$ is not infinitesimally small, usually do not exceed 2 or 3 percent. The separation between the potential electrodes, M and N, is always less than one-fifth the separation between the current electrodes, A and B, and is usually kept less than one-tenth this distance.

THEORETICAL CURVES

In Fig. 4 are shown the equipotential lines on the surface of the earth around a point source of current over a contact dipping 45°. The reflection coefficient K is 0.8. The units of potential are arbitrary. Along the outcrop of the dipping contact, for arbitrary dip and resistivity contrast, the potential is inversely proportional to the inter-electrode distance R:

$$V = \frac{I\rho_1(1 + k)}{2[\pi - k(\pi - 2\alpha)]R}. \tag{26}$$

At large distances from the source, the equipotential lines are circles described by the same formula. In the case of Fig. 4, we have

$$V = \frac{3I\rho_1}{2\pi R}. \tag{27}$$

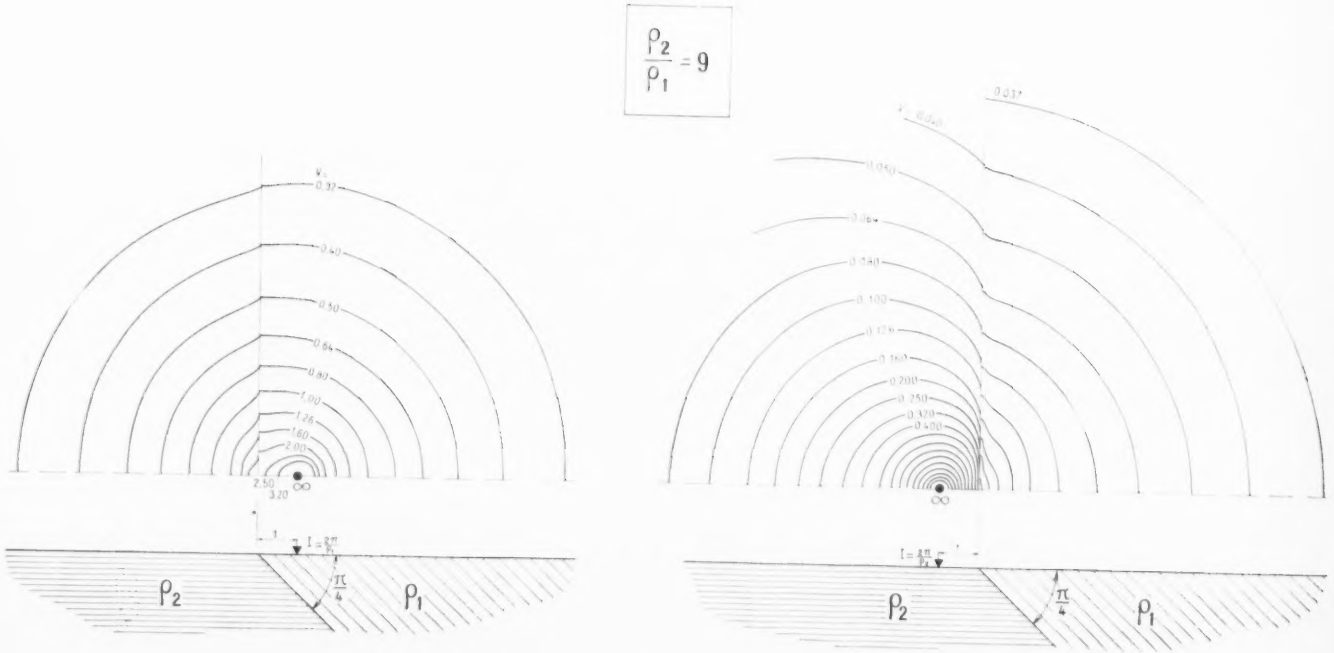

FIG 4. Equipotential lines due to a point electrode near a bed dipping at 45°.

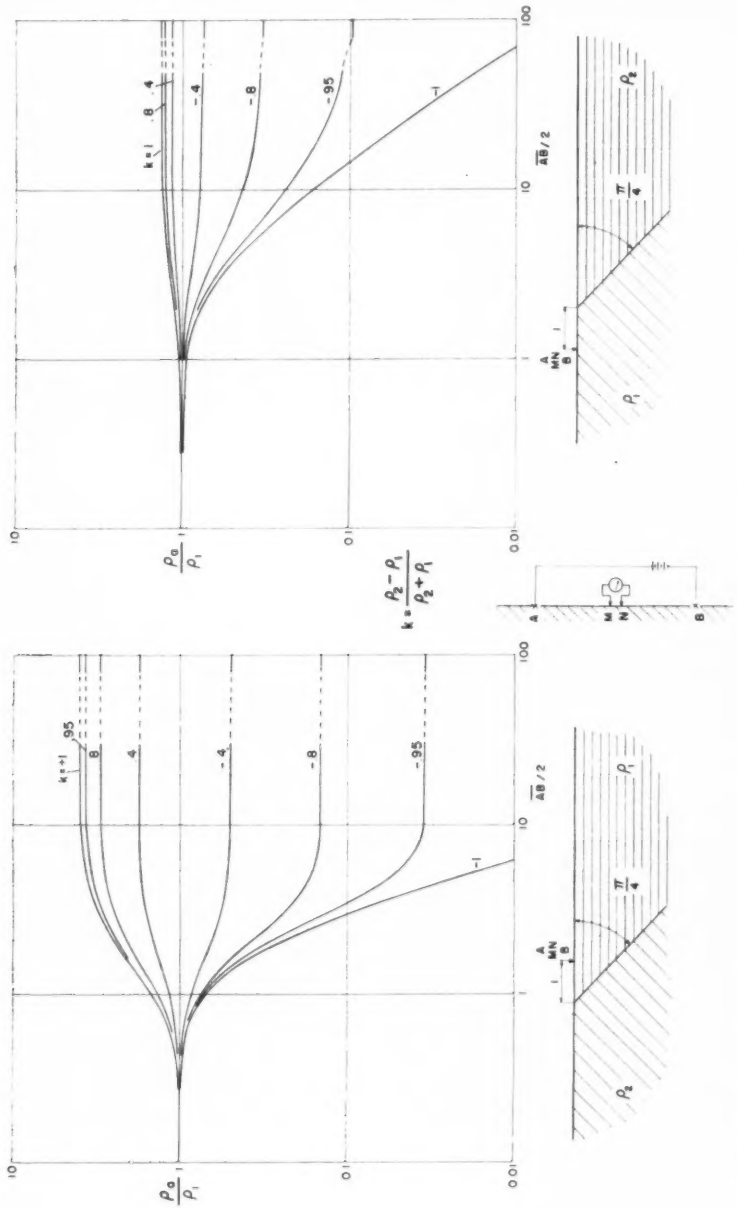

FIG. 5. Vertical profiles with Schlumberger configuration oriented parallel to the strike of a contact which dips 45°.

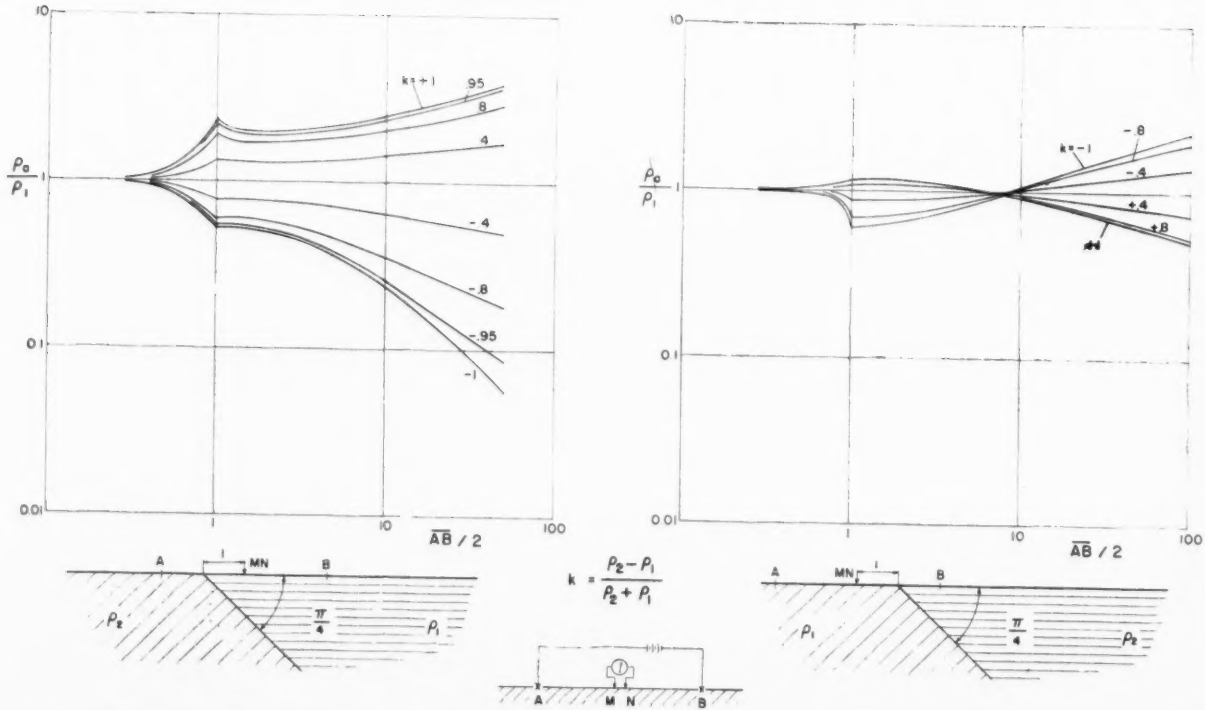

FIG. 6. Vertical profiles with Schlumberger configuration oriented perpendicular to the strike of a contact which dips 45°.

Formula 26 can be derived from elementary considerations (Sûmi, 1953) or by considering the limiting case of either of equations 12 (Maeda, 1955).

Fig. 5 shows vertical profiles made with the Schlumberger configuration oriented parallel to the strike of the dipping contact. Electrode separations are measured in units of the distance from the outcrop of the dipping contact to the line of electrodes. As would be expected, the effect of the dip is considerably less when the traverse is on the up-dip side than when it is on the down-dip side of the dipping contact.

The resistivity is plotted in both cases as the ratio ρ_a/ρ_1 where ρ_1 is the resistivity of the medium containing the electrodes—or, in this instance, the whole configuration. If the resistivity were instead plotted on an absolute scale, the asymptotic values for large electrode separations would be the same, for a given resistivity contrast, regardless of on which side of the contact the electrodes are placed. This statement is true only if the line of electrodes is oriented parallel to the strike of the contact. The reason is that the parallel component of the electric field must be continuous across the boundary. As the electrode separation increases, the configuration moves relatively closer to the boundary. Since ρ_a here is calculated from the electric field, it follows that ρ_a must be the same on both sides of the fault when the configuration is parallel to the strike and the electrode separation is large.

Fig. 6 shows vertical profiles taken with the Schlumberger configuration oriented perpendicular to the strike of the fault plane. Electrode separations are measured in units of the distance from the surface trace to the center of the configuration. Due to the geometry of the electrode configuration itself, these curves are paradoxical in that the apparent resistivity approaches either infinity or zero, for large electrode separations, in all of these curves. Let us consider only the case which $\rho_2 > \rho_1$ ($k > 0$). As would be expected, for small electrode separations the curves start out with $\rho_a = \rho_1$; and, as the electrode separation is increased, the apparent resistivity increases until the east current electrode reaches the contact. At this electrode separation, the apparent resistivity is intermediate between ρ_1 and ρ_2. For increasingly larger electrode separations, the apparent resistivity decreases asymptotically to zero.

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GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 794-814, 15 FIGS.

A PRELIMINARY REPORT ON MODEL STUDIES OF MAGNETIC ANOMALIES OF THREE-DIMENSIONAL BODIES*

ISIDORE ZIETZ† AND ROLAND G. HENDERSON†

ABSTRACT

Model experiments were made to devise a rapid method for calculating magnetic anomalies of three-dimensional structures. The magnetic fields of the models were determined using the equipment at the Naval Ordnance Laboratory, White Oaks, Md. An irregularly shaped mass was approximated by an array of prismatic rectangular slabs of constant thickness and varying horizontal dimensions. Contoured maps are being prepared for these magnetic models at different depths and for several magnetic inclinations. The fields of these three-dimensional structures are obtained by superimposing the appropriate contoured maps and adding numerically the effects at each point. The equipment and laboratory methods are described. Theoretical and practical examples are given.

INTRODUCTION

In the method of aeromagnetic interpretation presented by V. Vacquier and others (1951) it was assumed that anomalies of large amplitude and covering large areas are due to changes in susceptibility within the basement complex. The effect of relief on the crystalline rock surface was neglected because the magnetic field produced by relatively small masses would be comparatively negligible and the time for computations would be disproportionately long. In this report, a rapid method has been devised for the calculation of the basement relief by using contoured field maps of magnetic prismatic models, which have been experimentally determined. This method may also be applied to calculate the magnetic field of most three-dimensional distributions.

Studies of the calculation of two-dimensional magnetic and gravitational fields are abundant. On the other hand, the available literature for the three-dimensional case is sparse. Some of the more important articles are those by Ballarin (1948), Fisher (1940), Gassman (1951), Grant (1952) and Pirson (1940). There are two general approaches to the problem: analytic and synthetic. In the former, the data are analyzed directly to yield the approximate size, shape, and depth of a possible anomalous distribution. This method was adopted by Tsuboi and Fuchida (1938) who determined the topographic mass distribution resting on a horizontal plane surface of known depth by a direct analysis of the gravitational field. They replaced the irregular distribution by a thin slab of material in which the density at any point is directly proportional to the elevation above the plane surface. This density distribution and the observed gravity anomalies are then developed separately into double Fourier series. A simple mathematical relationship between the coefficients of similar terms in the expansions results ultimately

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in the anomalous topography. In recent articles Grant (1952) described a method which also uses the analytic approach. Briefly, the shape and size of the approximate structures are determined from dipole, quadrupole, and octupole moments which are calculated from the derivatives of the surface field. Peters (1949) has described a method developed by the Gulf Research and Development Company in which a series expansion of the field is used to calculate magnetic contours and ultimately topographic contours on the basement.

The synthetic method is an indirect one, involving trial and error. The field is calculated for an assumed disturbance of given size and shape on a surface at known depth and the calculated field compared with the observed anomaly. By judiciously altering the dimensions of the assumed body, a fit of the required accuracy can be obtained. Pirson (1940), Gassman (1951), and Lancaster-Jones (1929) have adopted this method using graphical aids whereas Roman (personal communication) makes use of numerical devices. In this paper an alternative approach using model experiments is described.

Apparently few magnetic model experiments have been made for use in geophysical interpretations. Heiland (1940) describes several experiments which are useful for qualitative interpretations. Alldredge and Dichtel (1949) discuss a model experiment to determine the basement topography of Bikini Atoll. Helmholtz coils were used to simulate the uniform inducing field of the earth. The model, resting on plywood, was molded by mixing foundry clay, ground magnetite, linseed oil, and glycerine. The magnetic anomaly produced by the model was detected by a miniature magnetometer, with a precision of ± 50 gammas, carried at a fixed height above the model by an automatic transverse system. The model, which was kept soft by the glycerine content, was reshaped until the model field compared favorably with the observed field.

ASSUMPTIONS AND BASIC CONSIDERATIONS

The airborne magnetometer in use by the U. S. Geological Survey measures the total intensity field. However it has been shown (Hughes and Pondrom, 1947) that for sufficiently small areas the direction of the anomalous total field can be assumed to be codirectional with the earth's ambient field. It is assumed furthermore that the anomalous field is due to induction by the earth's field only and that the effects resulting from remanent magnetization not codirectional with the earth's field can be considered negligible. For bodies possessing comparatively large permanent magnetization in directions other than that of the inducing field, the method described herein is not applicable. For most situations the aforementioned assumptions seem reasonable.

Any irregularly shaped body (Fig. 1) can be approximated by the proper arrangement of prismatic rectangular slabs of constant thickness and varying horizontal dimensions. If contoured total-intensity magnetic fields of numerous slabs were made available, having the geometries mentioned above, buried at different depths, and for several magnetic inclinations, then for an irregular

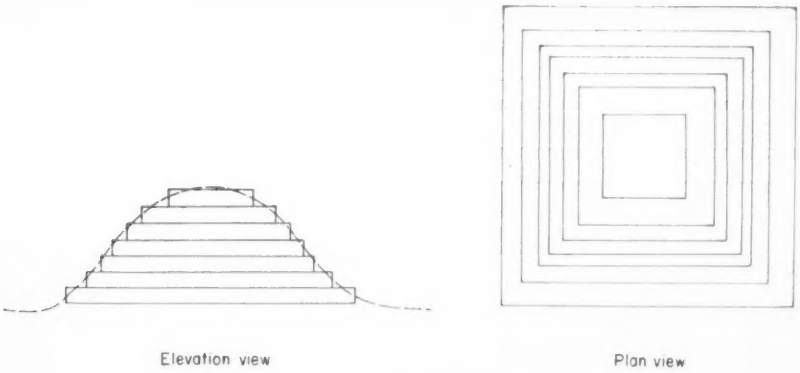

FIG. 1. Approximation of a three-dimensional structure by prismatic slabs.

magnetic mass distribution, the field could be obtained by superimposing the appropriate contoured maps and adding numerically the effects at each point.

MODEL EXPERIMENTS

The model experiments described in this preliminary report were conducted at the Naval Ordnance Laboratory, White Oaks, Maryland, with the cooperation of L. R. Alldredge, Chief of the Electricity and Magnetism Division of the Physics Research Department. Invaluable technical assistance was provided by C. L. Parsons and K. E. Dornstreich, also of the N. O. L., who helped us adapt the existing equipment to our particular problem. Much of the experimental work was done by R. L. Faith, R. W. Bromery, G. B. Mangan, and H. L. Crumley of the U. S. Geological Survey.

Measurements were made (Fig. 2) in a building constructed entirely of nonferrous material, which houses huge Helmholtz-type coils whose axes are mutually perpendicular. The coil system establishes a uniform field of known direction and intensity at the center of the system. With the aid of an elaborate potentiometer arrangement the field can be impressed with an accuracy of 0.1 milligauss or 10 gammas. In these experiments the magnitude of the inducing field for all magnetic dips was maintained at 53,400 gammas.

The principle of detection is similar to that employed in the AN/ASQ-3A airborne flux-gate type magnetometer (Rumbaugh and Alldredge, 1949) in that it has a saturable core inductor which makes use of the variation of permeability with intensity of magnetization. A narrow band-pass filter permits only the passage of the second harmonic component generated in the inductor. The signal generated in the detector is amplified and recorded as a continuous profile on a Speedomax recorder. Unlike the AN/ASQ-3A, the detector is not self-orienting but is kept fixed in the direction of the inducing field.

As the magnetic equipment was built for use in the degaussing of ships, the detector was placed below the model. For geophysical interpretation, however, the experimentally derived fields are more useful if the detector is located above rather than below the magnetic source. The transformation is theoretically accomplished by rotating the recorded profile 180° about an axis normal to the paper and directly above the center of the model so that the observed negative anomaly becomes positive and the direction of the profile is completely reversed, i.e., for a north-south profile the north end is rotated into the south end and for an east-west profile, the east end is rotated into the west end.

The model is placed on a fixed tray in the center of the system. The detector is below the model on a vertical tower and is capable of moving continuously in

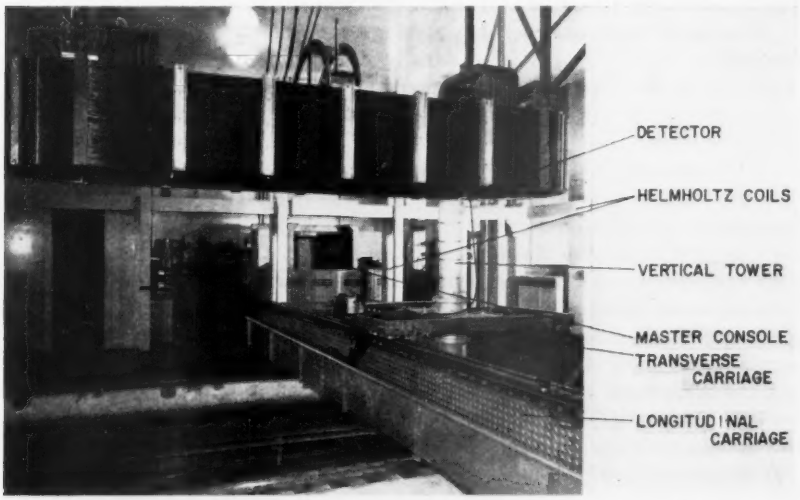

FIG. 2. Magnetic laboratory at the Naval Ordnance Laboratory, White Oaks, Maryland.

either a north-south or east-west direction. This is made possible by an automatic traverse system which includes 2 carriages run over brass rails, the lower pair being anchored to concrete piers. As indicated in Figure 2, the longitudinal carriage moves along rails in a north-south direction whereas the transverse carriage mounted on top of the longitudinal carriage moves along rails in an east-west direction. Control of this traverse mechanism as well as the potentiometers and the speedomax recording equipment is affected through a master console which can be operated by a single individual (Fig. 2). Sufficient profiles were run to permit adequate contouring of the field. A synchro-servo gear box added to the recorder permits synchronization of the chart paper with the detector motion. The magnitude of the induced field is reduced by means of a direct suppression current permitting a maximum sensitivity of 10 gammas per scale division.

To determine the accuracy of the profiles the same lines were run in opposite directions; differences of less than 3 gammas for the total length of line were found.

The models were demagnetized by *shaking* in a null magnetic ambient field with a 60-cycle alternating current of more than 50 amperes, maximum amplitude. A high coil constant of 8.8 oersteds per ampere was obtained by constructing a doughnut-shaped coil concentrically wound with inner and outer diameters of 10 and 40 cms respectively. As the inner diameter of the coil was much smaller than the horizontal dimensions of some of the models, the equivalent of a decaying field was obtained by fixing the coil and moving the model back and forth, gradually removing it from the magnetic field of the coil. The models were tested for remanence by taking profiles in a null inducing field.

The models were constructed by making a uniform mixture of 1 part powdered magnetite with 2 parts plaster of paris by volume. Water was added to form a uniform viscous mixture that was poured into carefully constructed forms. These were constructed with dimensional tolerances of 0.02 inch, of plywood sides and masonite bases.

The horizontal dimensions of the models were selected, in the main, for consistency with those presented in G. S. A. Memoir 47. The following horizontal dimensions (in inches) were chosen: 5×20, 5×30, 5×5, 10×30, 10×10, 20×20, $2\frac{1}{2}\times20$, 10×20. In order to reduce errors due to a non-uniform field in the detector coil, a minimum model-detector distance of 5 inches was chosen. The selection of a constant slab thickness of 0.5 inches, although somewhat arbitrary, was based primarily on the following considerations. The use of thinner slabs would improve the accuracy of the model approximations to three-dimensional structures. On the other hand this would increase the number of model field experiments which, from a practical viewpoint, should be kept to a minimum. A compromise for the slab thickness of 0.5 inches was finally adopted. However, this necessitated the measurement of fields for model depths at intervals of 0.5 inch. Consequently, it was planned to measure the magnetic fields in a horizontal plane for a minimum distance of 5 inches to a maximum distance of 10 inches in 0.5 inch steps. As the horizontal dimensions of the models published in G. S. A. Memoir 47 are measured in terms of the depth of burial, a prism 30 inches $\times$ 5 inches $\times$ 0.5 inches at a depth of 5 inches is magnetically equivalent to a $6\times1\times0.1$ prism expressed in terms of unit depth. Fields were mapped with the long axis oriented first parallel and then normal to magnetic north. The magnetic dips of the inducing fields were taken to be $I=0°$, 20°, 30°, 45°, 60°, 75°, and 90° which, again, is consistent with the inclinations selected in the memoir. This spread of dip angles makes the interpretive method applicable in most areas.

COMPILATION

Profiles were taken in a north-south direction because the *background* or regional gradient was small in magnitude and essentially linear in that direction.

Thus the background could be accurately determined by a graphical linear approximation. This is best illustrated by considering Figure 3. The profile represents the field measured by the detector along a north-south line 7 inches above the center line of a 10 inch×10 inch model subjected to a 60° inducing field. The *background* field *OB'* was determined by removing the model and measuring the field along the same line subject to the same ambient field. This gradient, of course, is removed in the compilation process. It is essentially the same gradient that would have been obtained by linear approximation. The removal of a nonlinear regional gradient was effected by experimentally determining the back-

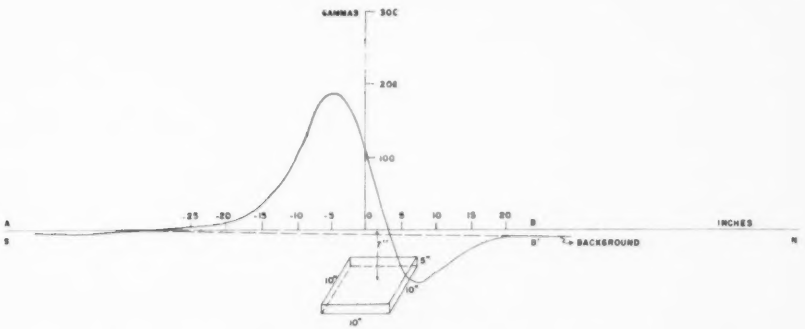

FIG. 3. Magnetic profile and *background* over midsection of 10 inch×10 inch×0.5 inch model located at depth 7 inches in an inducing field of inclination, 60°.

ground field and subtracting graphically from the original profile. A few east-west lines were run as tie lines. The profiles were spaced sufficiently close to give an accurate representation of the field.

The compilation of a set of profiles for a particular set of conditions is straightforward. The contour interval is arbitrarily selected as 10 or 20 gammas depending on the amplitude of the anomaly, and the position of the observed values plotted along the line of traverse. To maintain a smooth field, the contours drawn will necessarily deviate from the observed values. In general the error introduced is much less than one-half a contour interval. This is an error which seems to be inherent in the compilation of data based on continuous profiling, when the profile separation is sufficiently small. The contoured field of a 5 inch×5 inch model in an inducing field of inclination $I=60°$ and located 5 inches below the detector is illustrated in Figure 4. The original values are shown to indicate some of the errors introduced in the compilation process.

As an additional check on the accuracy of the field measurements, the fields of two models were arithmetically combined to produce a resultant field which could be compared directly with the observed field produced by the combined models. The effect of a 5 inch×20 inch model with the long axis oriented north-

south at a depth $d = 5$ inches for an inducing field of $I = 0°$ was computed by considering two $2\frac{1}{2}$ inch$\times$20 inch models placed in juxtaposition. The comparison was made in tabular form (Table 1) for several points on the profile 3 inches west of the midsection in a north-south direction. The average error is approximately 13 gammas. The discrepancy may be attributed, in part, to different demagnetization factors corresponding to each of the two different prismatic shapes. This is discussed in a later section. Furthermore, the magnetic susceptibilities of the prisms are not identical.

After several months work at the laboratory it became evident that the operat-

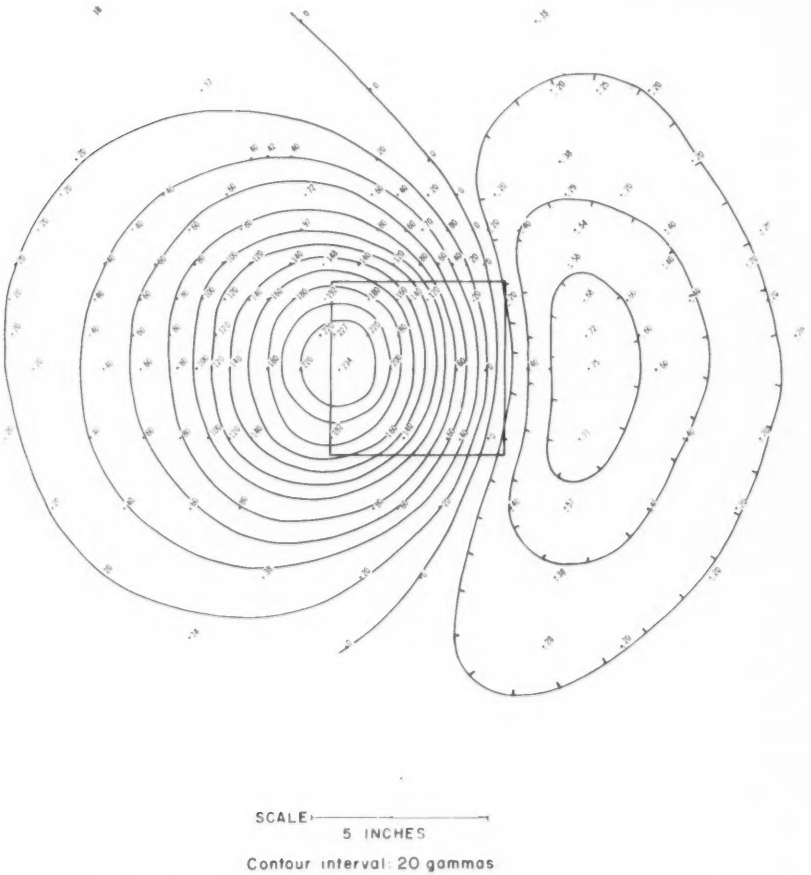

FIG. 4. Total-intensity magnetic field of a 5 inch$\times$5 inch$\times$0.5 inch model located 5 inches below the surface, in an inducing field of 60°.

ing time would be prohibitively long. Consequently it was decided to determine the fields very accurately for all models located at depths of only five and eight inches. The fields at intermediate levels were to be computed by employing the mathematical process of analytical field extensions which has been adequately described in the literature [e.g. Henderson and Zietz 1949]. An investigation was conducted to test the accuracy of the extensions. Several anomalies were computed upward and compared with the observed values. In almost every case,

TABLE 1

COMPARISON OF FIELD OF 5 INCH×20 INCH×0.5 INCH MODEL WITH THAT OF A SIMILAR MODEL OBTAINED BY THE JUXTAPOSITION OF TWO 2½ INCH×20 INCH×0.5 INCH MODELS

Values are obtained for points along a north-south line 3 inches west of the midsection of model located at a depth, $d=5$ inches, in an inducing field of inclination, $I=0°$.

Location of Point (Distance from center, in inches)	Combined Field (gammas) derived from two 2½ inch×20 inch ×0.5 inch models	Field (in gammas) of 5 inch×20 inch ×0.5 inch model	Error (in gammas)
0	−150	−158	+ 8
2	−150	−163	+13
4	−152	−170	+18
6	−146	−163	+17
8	−108	−123	+15
10	− 24	− 40	+16
12	53	60	− 7
14	69	83	−14
16	65	73	− 8
18	40	53	−13
20	25	40	−15

the error involved was ten gammas or less. Typical comparisons are given in Table 2. In these illustrations all comparisons are made for points along the midsection of the models.

At the present writing, all observed data for models at depths of 5 and 8 inches have been compiled. The extension of fields for the intermediate depths is now well under way.

NORMALIZATION PROCESS AND DEMAGNETIZATION EFFECTS

For these maps to have greater utility a *normalization* process will have to be applied. It is clear that the induced anomalous fields contain the parameters of the inducing field and the susceptibility of the magnetizable material. Consequently by eliminating these factors, a new quantity is obtained which is dependent only on the geometry of the magnetic mass.

Consider a fixed righthanded rectangular coordinate system (x, y, z) with the z axis directed downward (Figure 5). The total intensity magnetic anomaly at point $P(x, y, z)$ can be expressed as

$$\Delta T(x, y, z) = kTf(x, y, z, x', y', z')$$

TABLE 2.

COMPARISON BETWEEN OBSERVED AND COMPUTED FIELDS AT POINTS ON PROFILES LOCATED ABOVE THE MIDSECTION OF THE MODEL.

Computed field is analytically determined from data at a lower level. All field data are expressed in gammas.

Model: 5 inch×20 inch×0.5 inch; $I=75°$
Field at $D=10$ inches. ΔT_0=observed.
ΔT_c=computed from data at $D=8$ inches.

ΔT_0	ΔT_c	$\Delta T_0-\Delta T_c$
5	7	−2
8	10	−2
13	13	0
18	20	−2
24	25	−1
31	34	−3
37	38	−1
39	40	−1
35	35	0
23	25	−2
12	10	+2
−2	−5	3
−6	−10	4
−7	−11	4
−5	−9	4
−3	−6	3

Model: 10 inch×10 inch×0.5 inch; $I=75°$
Field at $D=8$ inches. ΔT_0=observed.
ΔT_c=computed from data at $D=5$ inches.

−18	−19	+1
−3	−2	−1
18	25	−7
58	62	−4
110	101	+9
150	150	0
168	172	−4
170	170	0
143	145	−2
103	112	−9
73	77	−4
43	50	−7
30	29	+1

Model: $2\frac{1}{2}$ inch×20 inch×0.5 inch; $I=90°$
a) Field at $D=7$ inch. ΔT_0=observed. ΔT_c=computed from data at $D=5$ inches.
b) Field at $D=9$ inches. ΔT_0=observed. ΔT_c=computed from data at $D=8$ inches.

	ΔT_0	ΔT_c	$\Delta T_0-\Delta T_c$
a)	18	16	+ 2
	30	33	− 3
	63	66	− 3
	90	85	+ 5
	105	113	− 8
	118	122	− 4
	120	129	− 9
	124	135	−11
b)	13	10	+ 3
	30	22	+ 8
	43	36	+ 7
	56	51	+ 5
	65	62	+ 3
	70	70	0
	73	74	− 1
	75	76	− 1

Model: 5 inch×5 inch×0.5 inch; $I=60°$
a) Field at $D=9$ inches ΔT_0=observed. ΔT_c=computed from data at $D=8$ inches.
b) Field at $D=10$ inches ΔT_0=observed. ΔT_c=computed from data $D=8$ inches.

	ΔT_0	ΔT_c	$\Delta T_0-\Delta T_c$
a)	3	4	−1
	8	10	−2
	14	12	+2
	21	19	+2
	28	28	0
	40	38	+2
	52	50	+2
	57	57	0
	52	54	−2
	34	36	−2
	13	14	−1
	−5	−8	3
	−14	−18	4
	−14	−18	4
	−8	−10	2
b)	5	7	−2
	8	10	−2
	13	13	0
	18	20	−2
	24	25	−1
	31	34	−3
	37	38	−1
	39	40	−1
	35	35	0
	23	25	−2
	12	10	+2
	−2	−5	3
	−6	−10	4
	−7	−11	4
	−5	−9	4
	−3	−6	3

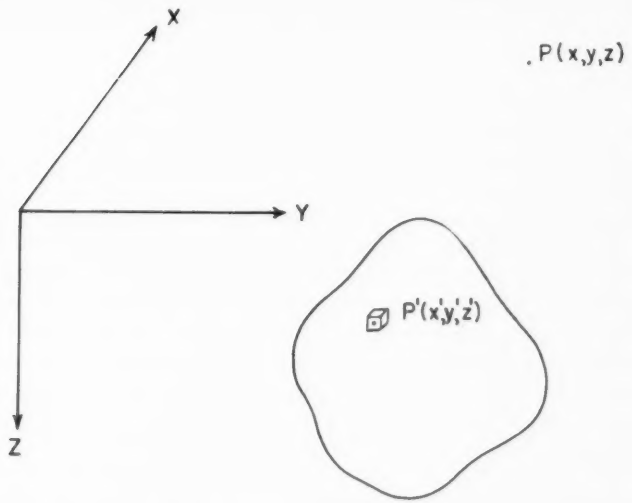

FIG. 5. Coordinate system used in evaluating magnetic fields.

where k is the susceptibility, T the magnitude of the inducing field and the primed coordinates represent coordinates in the body. As previously mentioned, ΔT and T are codirectional. For a point at the origin, the field becomes:

$$\Delta T(0, 0, 0) = kTf(x', y', z') \tag{1}$$

By forming:

$$\frac{\Delta T(0, 0, 0)}{kT} = f(x', y', z')$$

a function is obtained which depends on the shape of the body only in relation to the depth. It is into this form that all the maps will eventually be reduced. However, because of the presence of free poles on a magnetized surface, the inducing field is always diminished in the following way:

$$T = T' - NI \tag{2}$$

where T is the field actually existing inside the body, T' is the field present in the absence of magnetic matter, I is the polarization, and N is a demagnetizing factor, which depends only on the geometry of the mass. The factor, N, varies from zero for a thin rod parallel to the inducing field to 4π for a magnetic sheet perpendicular to the field. A sphere has a demagnetization factor of $4/3\ \pi$. By substituting the expression for T' given in equation (2), in equation (1), the following relationship is obtained.

$$\Delta T(0, 0, 0) = k'T'f(x', y', z') \tag{3}$$

where

$$k' = k/1 + Nk$$

The demagnetization factor, N, can be rigorously computed for any second degree surface since the field inside the body is uniform. It follows that the apparent susceptibility, k', of a magnetic mass can be derived from equation (3) provided the function $f(x', y', z')$ can be theoretically evaluated. The true susceptibility can then be calculated by considering the demagnetization factor, N. For materials with low susceptibilities, N plays a minor role and $k \sim k'$. Specifically for $k'=0.010$, $k=0.011$ and for $k'=0.015$, $k=0.018$. Unfortunately it was necessary to use higher susceptibilities ($k=0.06$) for the magnetic models under investigation in order to get a measurable response on the magnetometer. As a result, the demagnetization factor must be taken into account. This can be done by approximating the model with an ellipsoid whose demagnetization factors are tabulated in convenient form by J. A. Osborn (1945).

Perhaps a more satisfactory approach to the normalization process would be to compute theoretically the function $f(x', y', z')$ for the various slabs at the point where the field is a maximum. Then the entire field for a particular model set-up could be adjusted by determining the ratio required to make the observed ΔT_{max} fit the theoretical ΔT_{max}. The shape of the resultant field will, of course, be somewhat in error as N is not constant. To illustrate this normalization process, consider the observed and theoretical profiles presented in Figure 6. The former

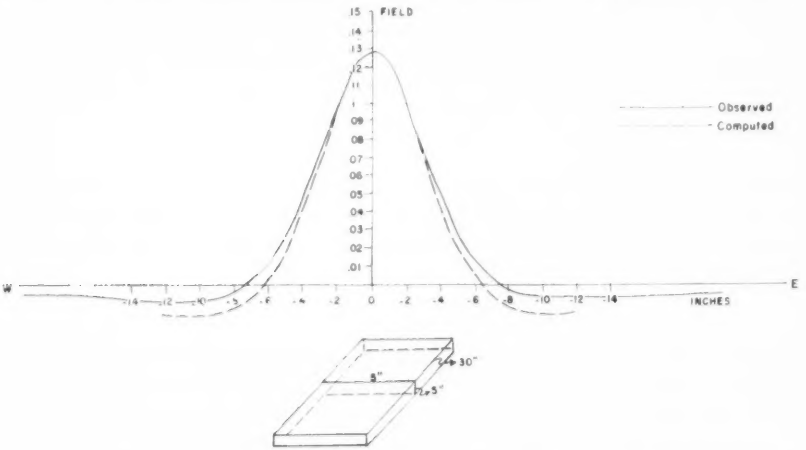

FIG. 6. Comparison of computed and observed east-west profiles over midsection of a 5 inch ×30 inch×0.5 inch model with long axis oriented north-south. Model is located 5.5 inches below detector and in a magnetic field of inclination, $I=90°$.

represents the normalized field along an east-west profile passing through the mid-section of a 5 inch×30 inch×0.5 inch model with the long axis oriented north-south. The model is located 5.5 inches below the detector and subjected to a vertical inducing field. As the length of the longer axis of the model is more than 5 times the depth of burial, theoretical calculations for the function $f(x', y', z')$ at points along the same profile as the observed, were made by approximating the model with a two-dimensional structure, namely 5 inch×∞×0.5 inches. At the maximum point, the ratio of the observed field, ΔT_{max}, to the polarization, $k'T'$, is made to coincide with the theoretical $f(x', y', z')$. This yields an apparent susceptibility of $k'=0.039$ which corresponds to a true susceptibility of $k=0.068$. The general shapes of the two curves agree favorably, the maximum discrepancy

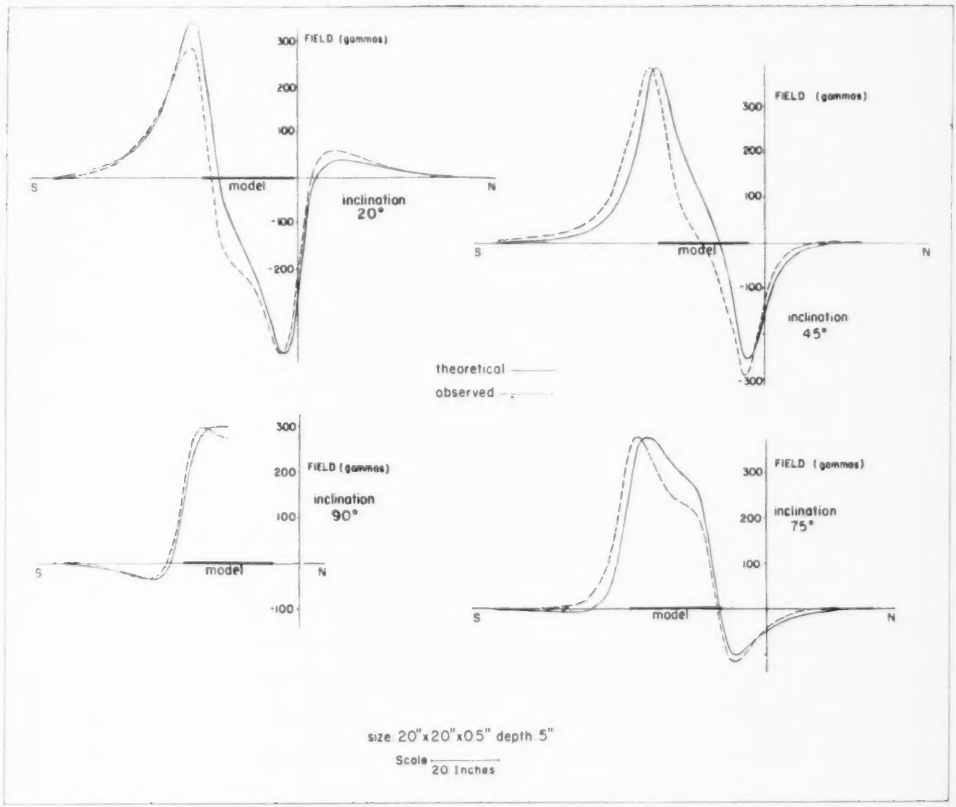

FIG. 7. Theoretical and observed profiles over the center of a prismatic model.

being equivalent to 20 gammas. Even this small difference may be explained by a two-fold consideration: first, the demagnetization factor is not constant and second, the assumption of an infinite slab is not strictly valid.

Theoretical north-south profiles for a 20 inch × 20 inch × 0.5 inch slab buried at a depth of 5 inches and subjected to inducing fields of inclination 20°, 45°, 75°, and 90° have been plotted and compared with the observed profiles (Fig. 7).

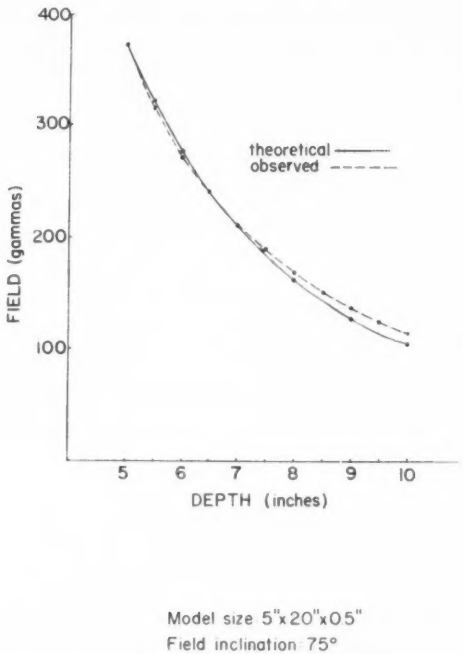

FIG. 8. Theoretical and observed values for points located at the same horizontal position plotted as a function of depth.

These curves show the amount of correction that would be necessary to apply to the observed data in order to correct for demagnetization effects. The profile corresponding to a dip of 90° is instructive since it shows, as one would expect, that the demagnetizing effect is a maximum near the center of the model.

Because the accumulation of free poles at the surface of the slabs depends only on the orientation of the inducing field with respect to the model, the demagnetizing factors should theoretically be independent of the distance from detector to model. This is verified by comparing theoretical and observed values as a function of detector to model depths (Fig. 8). The values are determined for points

located at exactly the same horizontal position near the maximum value. The maximum discrepancy is less than 10 gammas which may be attributed to errors in the experimental or compilation methods.

To obtain a reasonably accurate numerical evaluation of the susceptibility, two cylindrical models were constructed from the same mixture that was used for the prisms. The radius and length of one of the cylinders were 1.08 inches and 5 inches respectively and those of the other were 2 inches and 5 inches respectively. Both were located at a depth of 4.5 inches and subjected to a field of $I=90°$. Profiles passing through the projected centers of the models indicated apparent susceptibilities of $k'=0.065$ and $k'=0.058$.

Using the demagnetization factors calculated by Mann (Werner 1945) for

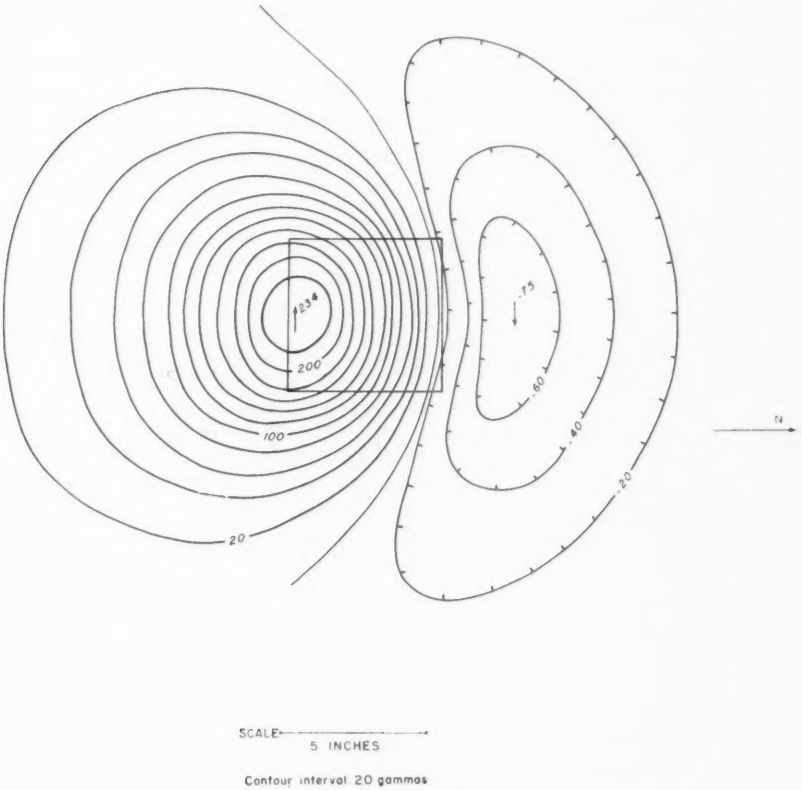

FIG. 9. Total intensity field of 5 inch×5 inch×0.5 inch model located at a depth of 5 inches below the plane of observation, in an inducing field of $I=60°$.

cylinders, the true susceptibilities were computed to be $k=0.069$ and $k=0.062$ respectively. These two values along with the one determined by considering a two-dimensional slab lead to a reliable average of $k=0.066$.

All the field maps will be made available in a "normalized" form, one which is independent of the susceptibility and field strength and dependent only on the geometry of the model. In this manner, complicated models may be built up by the proper combination of prisms and the total normalized field computed by arithmetically summing up at each point the normalized fields due to each of the prismatic slabs. Multiplication with the apparent susceptibility of the rock and the strength of the inducing field results finally in the desired magnetic field. Fortunately, in geophysical prospecting, the relative susceptibilities of most rocks under investigation are so small that the demagnetization factors can be neglected. For large susceptibilities, the demagnetization factor should be considered.

Although the compilation of the model field maps is well under way, we have not yet started the normalization process. It will prove instructive to examine the fields for a set of three maps already complied. Such a set is presented in Figures 9, 10, and 11, to illustrate the fields of a 5 inch×5 inch×0.5 inch model at depths

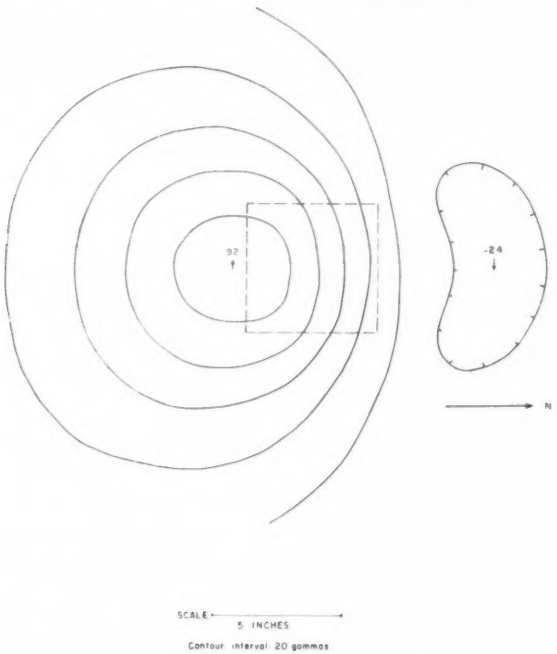

FIG. 10. Total intensity field of 5 inch×5 inch×0.5 inch model located at a depth of 7.5 inches below the plane of observation, in an inducing field of $I=60°$.

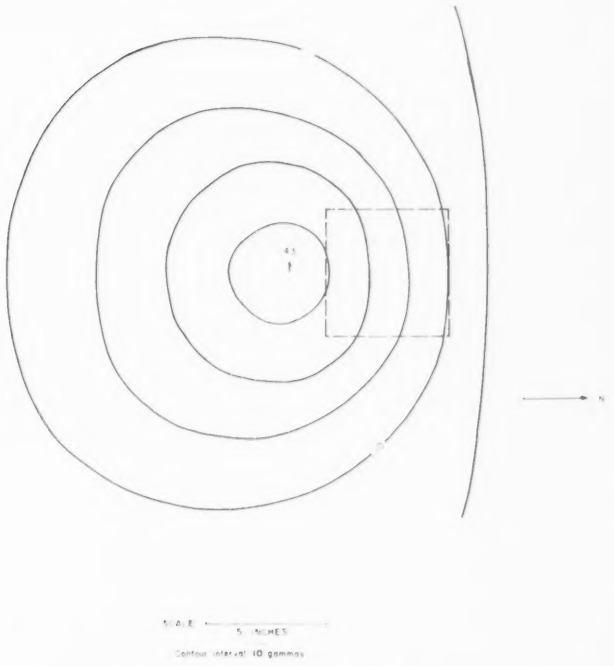

FIG. 11. Total intensity field of 5 inch×5 inch×0.5 inch model located at a depth of 10 inches below the plane of observation, in an inducing field of $I=60°$.

of 5 inches, 7.5 inches and 10 inches respectively. The inducing field is 53,400 gammas inclined 60° from the horizontal. The fields of the models at the 5 inch and 7.5 inch depths were complied directly from observations and the other field was theoretically determined by the process of analytical continuation. The general magnetic features of a mass distribution in a total intensity field are well illustrated. The maximum is displaced to the south of the center of the body and a well-defined minimum appears at the north. As the depth of burial of the model increases, the anomaly becomes broader, diminishes in amplitude and the maximum is displaced more and more to the south.

THEORETICAL AND PRACTICAL EXAMPLES

To illustrate the method of superposition of fields, an arbitrary theoretical field (Fig. 12) is built up using the calculated fields of several models all subject to inducing fields of inclination 60° and amplitude 53,400 gammas. The model dimensions and method of combination are indicated in the diagram. The susceptibility of the models is approximately 0.06 c.g.s. units. Demagnetization factors were not applied.

As a practical illustration demonstrating the method of interpretation, the magnetic anomaly over Great Sitkin Island, one of the volcanic islands near the middle of the Aleutian Islands, was selected for analysis. This is particularly suitable for analysis because the geometry of the anomalous magnetic mountain mass is known, thus permitting a comparison of the shapes of both computed and observed fields. Because no samples were obtained for susceptibility determinations, a theoretical average susceptibility will have to be assigned to the rocks in order to make the magnitudes of both observed and computed anomalies agree.

Great Sitkin island (Simons and Mathewson, 1947) is about 11 miles in diame-

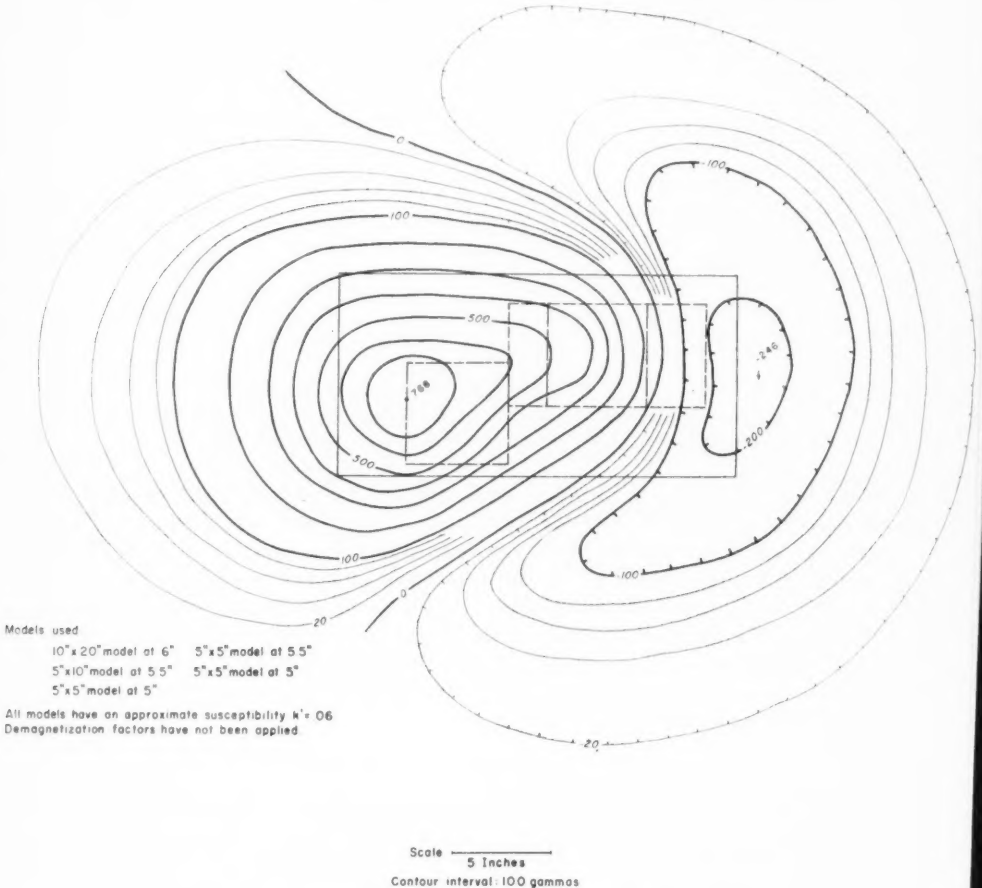

FIG. 12. Total intensity magnetic map resulting from a combination of model fields in an inducing field of 53,400 gammas and inclination 60°.

ter and rises to an average height of 4,500 feet except for a small peak of 5,740 feet on the east edge of the present vent. The oldest rocks exposed are the Finger Bay volcanics (Paleozoic?) which form the rugged headlands of the south and southeast coasts. The Sand Bay volcanics (Tertiary) form most of the southern half of the island and the Great Sitkin volcanics (late Tertiary and Quaternary) form the northern half of the island including the present cone. All the rocks of the island are either andesitic or basaltic with some alteration present in the oldest rocks.

An aeromagnetic survey over Great Sitkin was made by the U. S. Geological Survey in 1947 (Keller, Meuschke and Alldredge, 1954), at a flight elevation of 7,500 feet and flight spacing of approximately 1 mile. The resulting contoured map of the magnetic field shows a broad anomaly covering the entire island and more than 500 gammas in amplitude on which is superimposed several anomalies considerably smaller in both amplitude and areal extent. These smaller anomalies are probably due to igneous plugs which have intruded into the rocks and lithologic contrasts within the mountain itself.

In effecting the comparison between the observed and computed magnetic

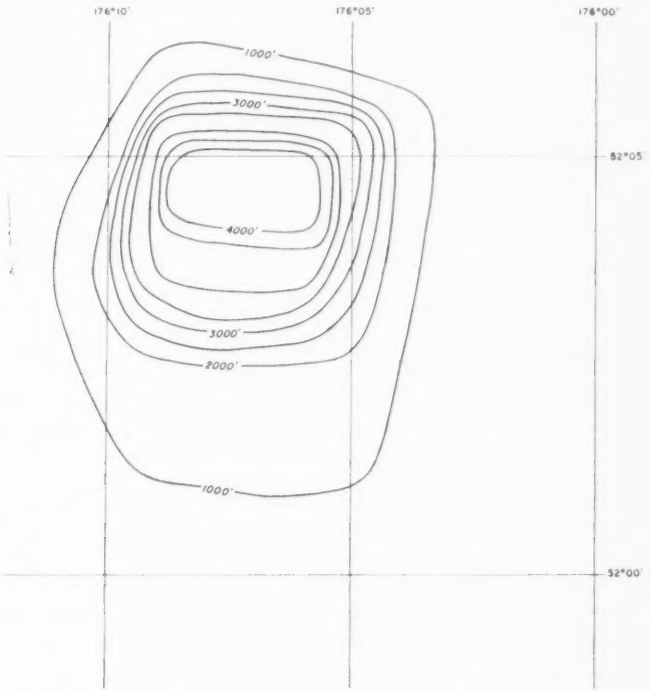

FIG. 13. Generalized topographic map of part of Great Sitkin Island, Alaska.

fields, two auxiliary maps were constructed. The contours representing the rugged topography of the island were replaced by smooth generalized contours in order to facilitate the selection of the models. This generalized map is given in Figure 13. Also, the smaller anomalies were removed on the magnetic map so that we may ascribe a uniform susceptibility to the huge volcanic mass. This smoothing process was effected by using the subjective method of *eye-balling* the contours. In this manner, a smooth regionalized contoured map (Fig. 14) was obtained which, in the main, represents the magnetic expression of the topography of the volcanic island. Through a careful consideration of the regional topographic map, appropriate models were selected and the calculated model fields superimposed, yielding the resulting magnetic field shown in Figure 15. Comparison between Figures 14 and 15 indicate excellent agreement considering the crudeness of the approximations.

A susceptibility of 0.01 c.g.s. units was assumed to obtain the proper amplitude. This value although slightly high for mafic rocks is not unreasonable, as magnetite was discernible in several hand specimens in this area (Simons and

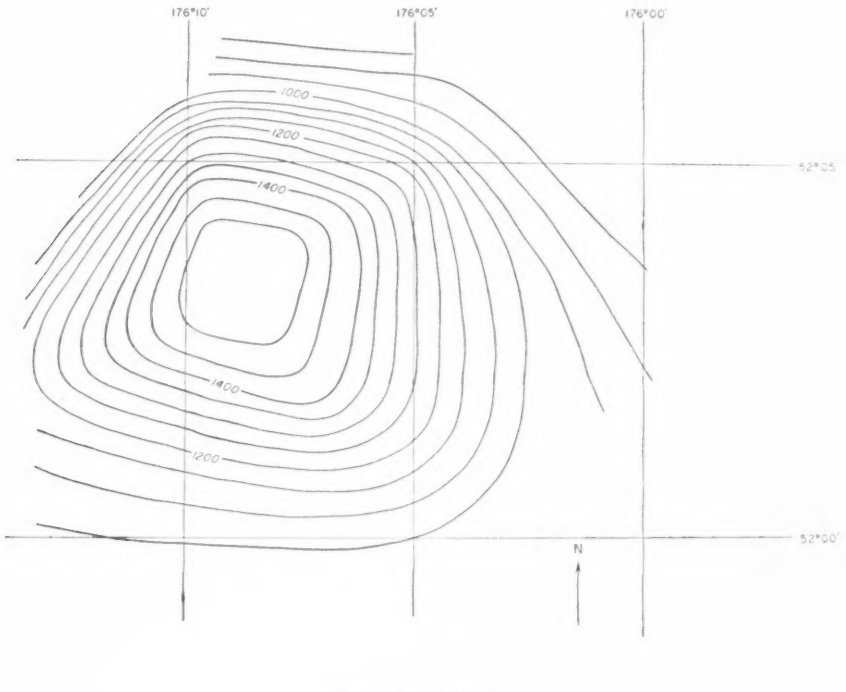

FIG. 14. Regional aeromagnetic map of Great Sitkin Island, Alaska.

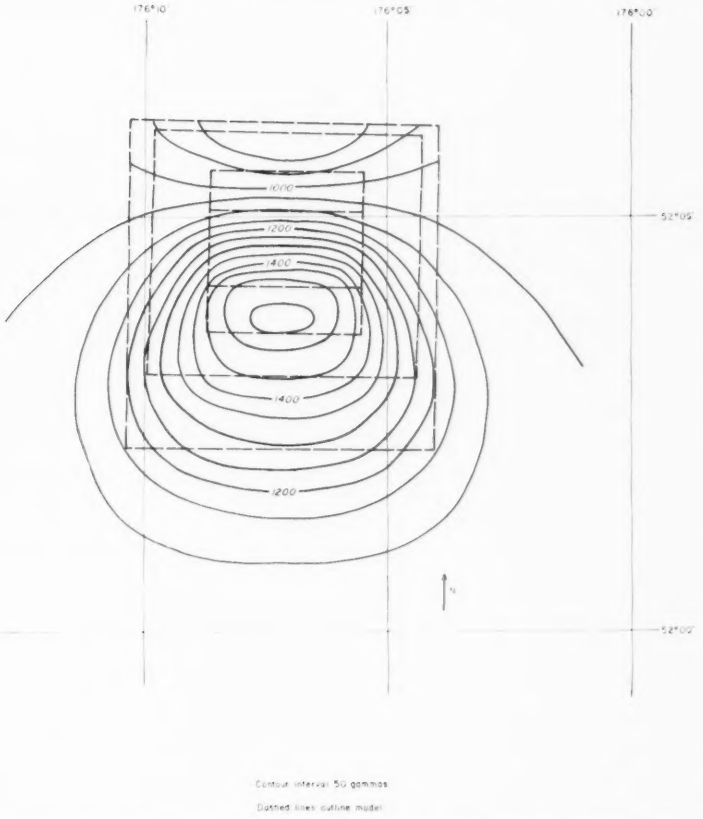

FIG. 15. Computed magnetic anomaly of Great Sitkin Island, Alaska using prismatic models.

Mathewson, 1947). As in the previous illustration the demagnetization factors were not applied.

SUMMARY AND CONCLUSIONS

The application of the model fields described presents an effective method for aeromagnetic interpretations involving three-dimensional structures. The anomalous field can be readily calculated by replacing the known distribution by the proper array of prismatic blocks and utilizing the *normalized* contoured maps of these blocks which will be made available as part of a final report. If the anomalous field is known, the distribution of blocks may be altered until a proper fit is obtained. Although the method lacks high accuracy, it has the advantage of allowing rapid calculations.

It must be emphasized that any interpretation of observed magnetic data

should be made cautiously because, in general, the solution is not unique. The susceptibility, the depth of burial, and the shape of the perturbing mass distribution all enter as parameters and the observed field may always be approximated by several combinations of these parameters. However, when two of these quantities are known, the third may be reliably determined.

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GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 815–827, 13 FIGS.

GEOPHYSICAL HISTORY OF PARENTIS OIL FIELD, FRANCE*

RAOUL VAJK† AND GEORGE WALTON‡

ABSTRACT

In 1951, the French Government granted an exclusive exploration permit to the Esso R.E.P. (a Standard Oil Company affiliate) over an area of 4,357,980 acres around Bordeaux in the northern part of the Aquitaine Basin, France. This area was investigated first by surface geology; then it was surveyed by the gravity meter. In checking the gravity anomalies by the reflection seismograph, a subsurface structure was found at Parentis in 1953, which was drilled in 1954, and was proved to be oil bearing. The Parentis oil field is the most important oil field, not only in France, but in all Europe outside the Iron Curtain.

Gravity map, seismograph map, seismic profiles, telluric map and geological contour maps, and cross sections of the Parentis structure are presented.

INTRODUCTION

In February, 1951, the French Government granted to Esso Standard, France, an affiliate of Standard Oil Company (N.J.) an exclusive exploration permit covering an area of 4,357,980 acres around Bordeaux, France (Fig. 1). This permit covers the northwestern part of the Aquitaine, or Bordeaux Basin, which lies immediately north of the Pyrenees mountains (Fig. 2). It is bordered to the north by the Massif of Brittany and to the northeast and west by the Massif Central. Geologically, this basin is open to the west to the Atlantic Ocean.

The southern part of the Bordeaux Basin is covered by the Permits of two French Companies, the Societe Nationale des Petroles d'Aquitaine (S.N.P.A.) and of the Regie Autonome des Petroles (R.A.P.).

A great number of wells were drilled during the last twenty years or so in the Bordeaux Basin, mainly in its southern part, for oil and other minerals. The only success in finding hydrocarbons was the discovery of the Saint Marcet gas field in 1939, and a small oil field at Lacq in 1949, both near the foothills of the Pyrenees.

Esso Standard, France, started its exploration in the Bordeaux Basin immediately after the Permit was granted. A surface geological survey and basin studies began early in 1951. A gravity meter survey was started on May 1, 1951, and was completed in May, 1952. An experimental telluric survey was carried out at the end of 1951 and during the spring of 1952. A few magnetometer profiles were run across the Permit and over to the margins of the basin in order to obtain some information as to the thickness of the sedimentary fill in the northern part of the Permit. The seismograph survey was started in 1952, immediately

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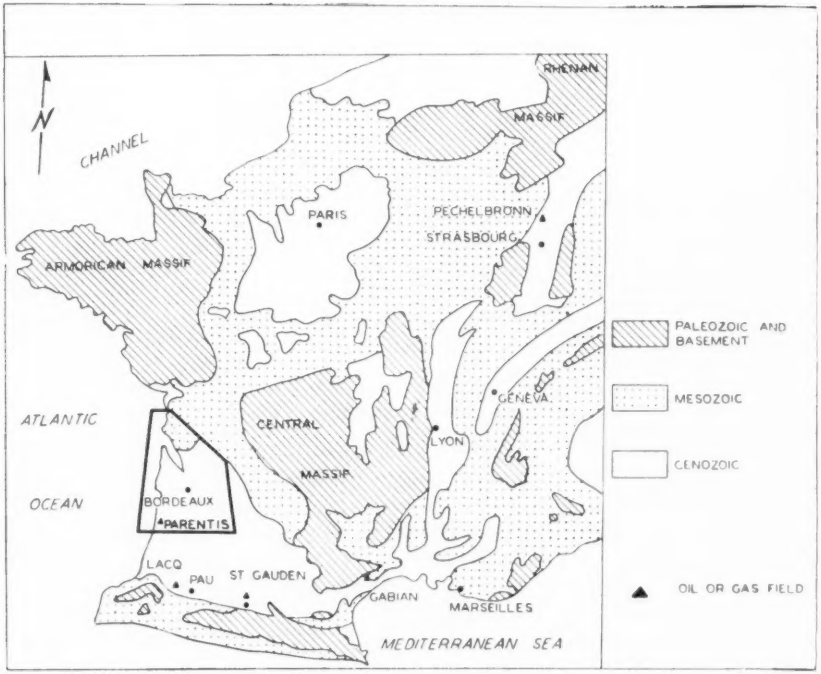

FIG. 1. Distribution of French sedimentary basins.

after the gravity survey was completed. This is still in progress, evaluating various parts of the Permit and detailing structures.

The basin studies and paleogeographical investigations indicated that the southern part of the Permit has a thick and probably rather complete sedimentary section and is therefore favorable for the occurrence of oil. Due to the lack of wells, no definite conclusions could be drawn for the basin development in the northern part of the area. Originally it was thought that the entire Permit area was relatively shallow. Later wells drilled in the southern part of the area, especially the deep test at Roquefort just below the southern border of the Permit, changed this conception considerably.

THE MAGNETIC SURVEY

The northern part of the area was still regarded as relatively shallow. The magnetometer profiles across the Permit showed very little change in the vertical component of the magnetic intensity (Fig. 3). This indicates that the igneous basement is probably at a considerable depth in the entire area of the Permit.

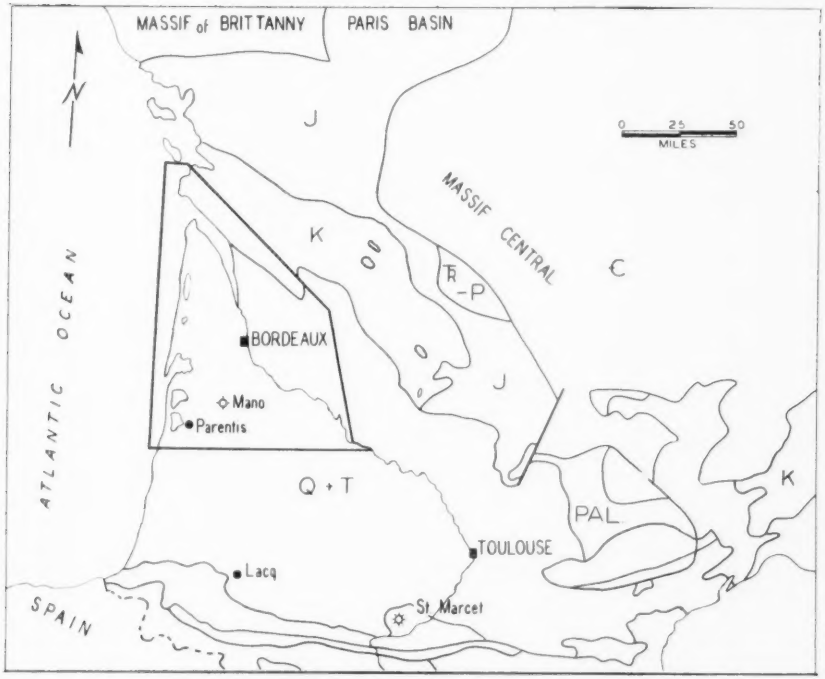

FIG. 2. Areal map of the Bordeaux Basin showing the location of the Permit area and the Parentis field.

However, a test drilled at Carcans, west of Bordeaux, found crystalline schists at the depth of 6,331 ft. This well is located on the top of a structure and the average depth to the basement must be greater than that depth. Anyway, it is a shortcoming of the magnetic method that it cannot distinguish between non-magnetic sediments and non-magnetic metamorphic rocks.

THE GRAVITY SURVEY

The gravity meter survey in the Bordeaux Permit is of a semi-detailed character. The gravity meter stations were located along lines four to five miles apart with an interval of about half a mile. Where an anomaly was found, it was detailed to the extent that it could be outlined and its importance determined.

All together, 8,807 gravity meter stations were made within the concession which corresponds to a station density of 1.2 stations per square mile. The Bouguer gravity map (Fig. 4) shows a large regional gravity minimum with the center near Libourne (east-northeast of Bordeaux) with a gravity value of −44

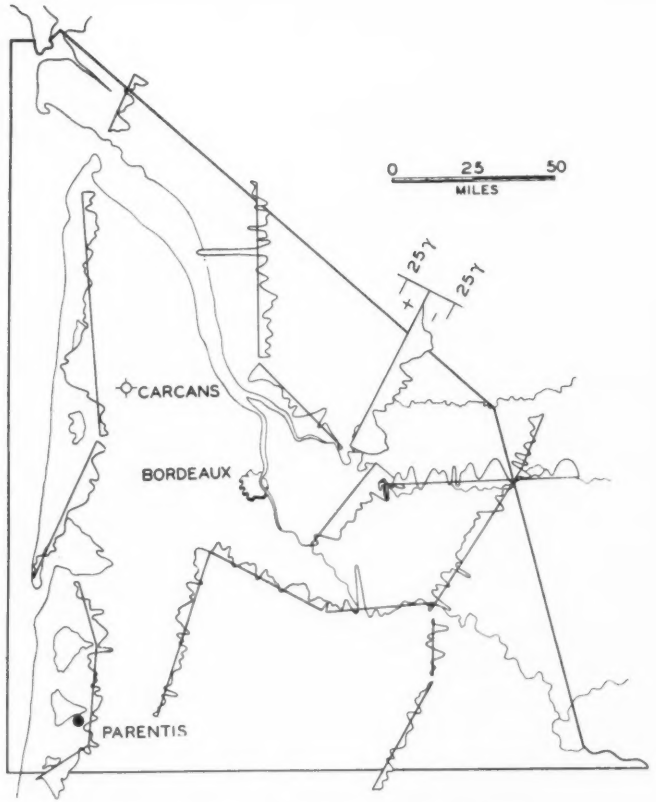

FIG. 3. Magnetic profiles in the Bordeaux Permit area.

milligals, which is the lowest gravity value within the Permit. The highest gravity value, +19 milligals, was observed at Mimizan in the southwest corner of the area.

From the Mimizan gravity high a gravity ridge strikes in an east-southeast direction across the Bordeaux Basin, dividing it into two regional gravity low areas. This suggests that the actual basin is divided geologically into two separate parts. However, the opinions of the geologists are still divided on this interpretation.

As can be seen on the gravity map, numerous gravity anomalies are indicated by the Bouguer isogams. Using a profile method, a residual gravity map was constructed. The southwestern part of the residual gravity map is shown in Fig. 5. The Mimizan gravity high, although considerably reduced in intensity,

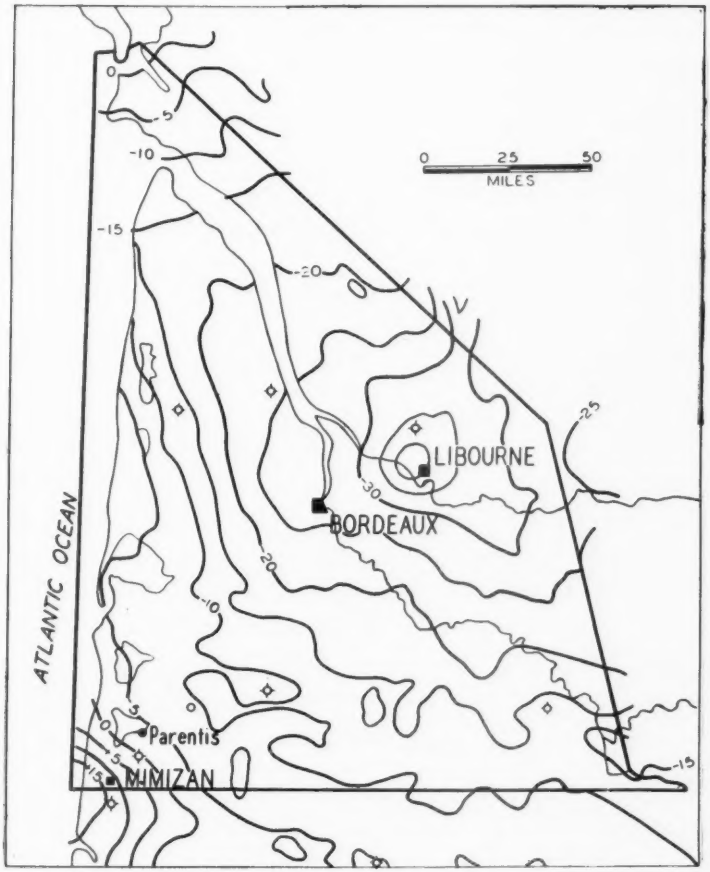

FIG. 4. Bouguer gravity map of the Bordeaux Permit area.

is still shown as a residual high. The northeast striking gravity nose adjoining the Mimizan gravity high is more pronounced on the residual map than it is on the Bouguer map, and its northeastern end turns toward the east. Several of the residual highs were checked by the reflection seismograph and this gravity nose was also investigated. This led to the discovery of the Parentis structure, which is, however, considerably displaced from this gravity nose and has an east-west strike instead of a northeast-southwest, as will be discussed later.

The first vertical derivative of the gravity was also computed and its anomalies in the southwest corner of the Permit area are shown on Fig. 6. The first

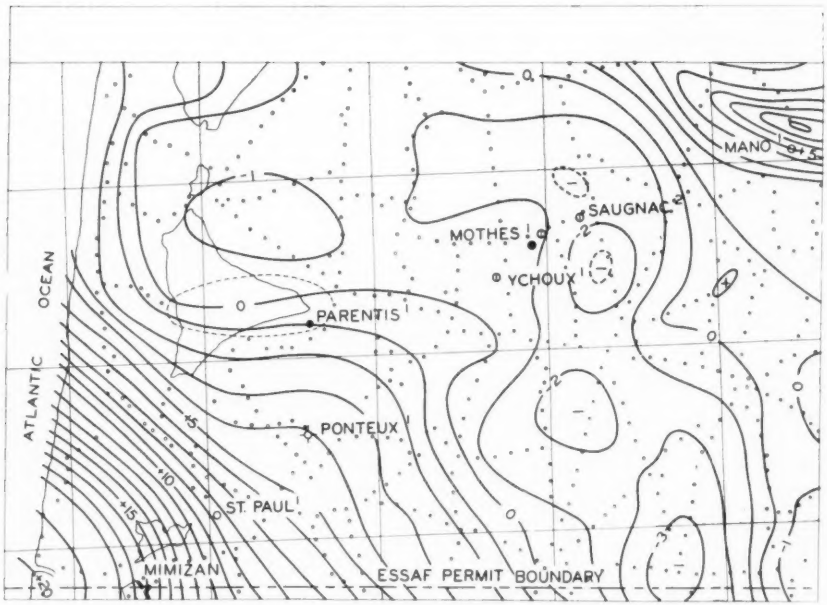

FIG. 5. Residual gravity map of the Parentis-Mano area.

derivative map shows also the Mimizan gravity high, but there is no indication on this map corresponding to the northeast striking gravity nose.

THE TELLURIC CURRENT SURVEY

The telluric current survey (Fig. 7) shows a weak positive anomaly along Lake Parentis, but its strike and position is different from those of the Parentis structure.

It should be mentioned here that the gravity and telluric anomalies gave a strong indication of the Mano structure which is located about 20 miles northeast of the Parentis structure. The Mano structure was confirmed by the seismograph and was drilled but was found barren. No satisfactory explanation can be offered for the failure of the gravity and telluric methods in the Parentis area.

SEISMOGRAPH SURVEY

Topography

The Parentis area is heavily wooded. It was originally a long sandy coastal waste, but was forested with Carolina resin pines during Napoleon's time. Parts of the area have been recently burnt over and are covered with thorny vegetation. These parts, due to the hidden stumps, constitute more of a field problem than

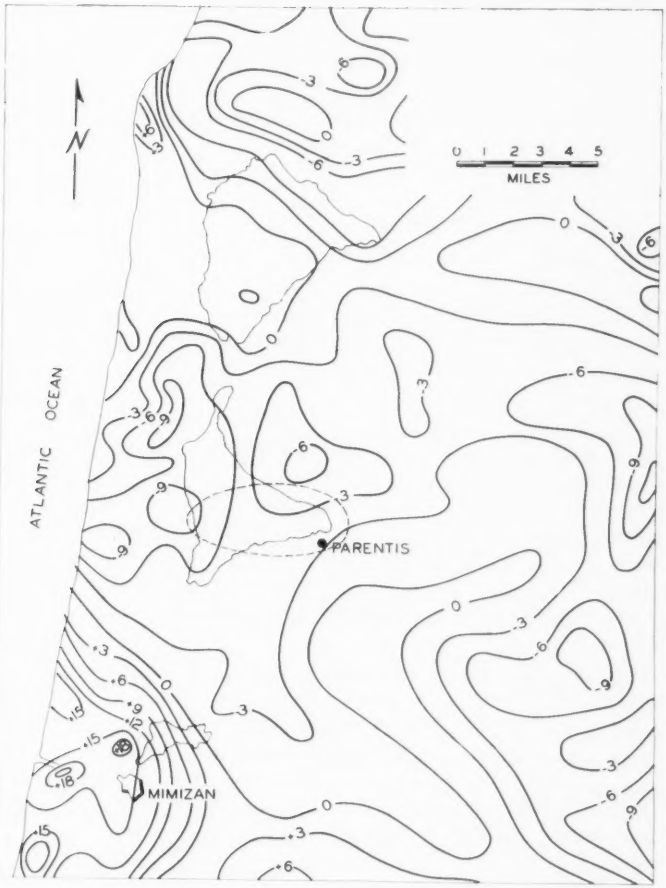

FIG. 6. First vertical derivative of gravity of the Parentis region.

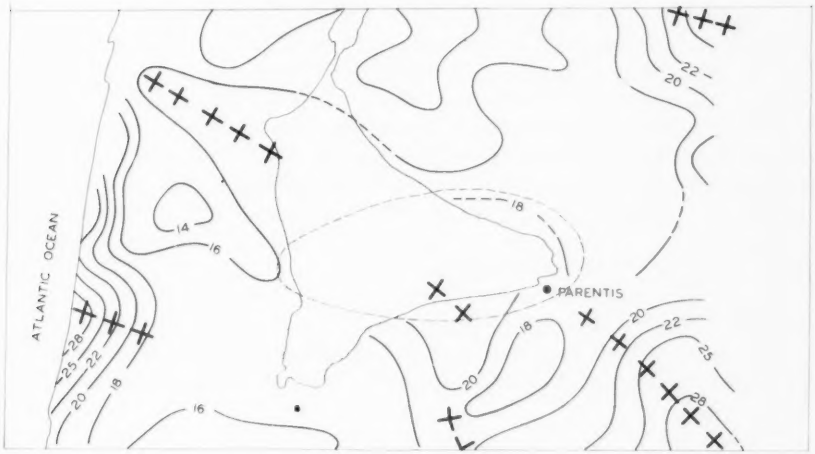

FIG. 7. Telluric survey of the Parentis area.

do the forests. The fire breaks in the forests were used for trails in the first seismic survey. Some portions of the area around Lake Parentis were poorly drained and were inaccessible at the time of the early shooting. The lake itself is fresh water fed by the surrounding local streams. It is a focus of attention as it lies directly over the axis of the Parentis anticline. It is difficult to see any relationship of the topographic expression in the form of this triangular lake to that of the underlying structure, yet the superposition is so obvious that it must give some reason for speculation. Artesian conditions were found in the shot holes on the east end of the lake near the location of the discovery well. Between the lake and the Atlantic Ocean is an area of sand dunes.

Field Technique

Esso Standard began seismic work in April, 1952, on Mano, gravity anomaly 20 miles northeast of Parentis. In that area it became necessary to use multiple holes and a star pattern of geophone arrangement in order to get useable reflection energy. As it has turned out, the starting point at Mano is probably the worst reflection area within the Permit. This was fortunate, as the same techniques required for getting results at Mano were successful in obtaining the deeper reflections at Parentis. Parentis is not a good reflection area, by ordinary standards.

The field work was done by C.G.G. (Compagnie Generale de Geophysique), an affiliate of the Schlumberger Corporation, under the supervision of Mr. H. L. Brewer of The Carter Oil Company. Most of the work was continuous profiling using a star pattern of 36 geophones per trace with shot holes spaced 870 ft.apart. This close spacing of shot holes was necessary for giving an intelligible seismograph record in view of the strong and erratic dips at depth in the presence of a great amount of subsurface interference on the records.

As already mentioned, the initial program was to check the most important gravity leads first, in order to make drilling locations for the evaluation of the area. The first line shot at Parentis was planned to cut across the residual nose on the large Mimizan gravity maximum. Although the center of the gravity feature does not lie on the Parentis structure, the first line was so placed as to pick up unmistakable evidence of anticlinal structure. Fortunately, the line was long enough. Seismic section (*A-A'*) Fig. 8 was the first one shot in this area. It is presented here to show the reflection distribution with depth. There is a concentration of energy in the first second of the records. The deeper reflection energy is actually much weaker in proportion on the records and lacks continuity. It is felt that it is entirely due to the use of pattern geophones here that this structure was found, as by their use there was less attenuation of reflection energy from the deeper horizons where the structure is developed.

Interpretation

The mapped horizon shows fair continuity on this particular section (Fig. 8). However, it did not lend itself to easy correlation. On succeeding sections it was

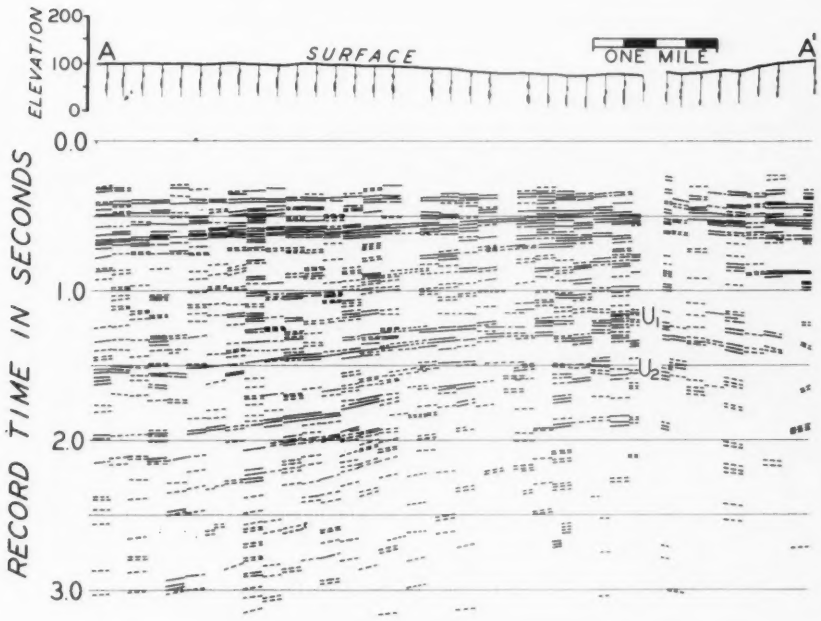

FIG. 8. Seismic cross-section of the Parentis anticline.

identified as the first well-defined reflection below the second unconformity. This, of course, assumed the persistence of the unconformities over the area. However, as there were many breaks in continuity on the lines, this means of identification was frequently relied upon. It proved to be dependable. Even on the later work, when there was still no tie between the shooting on the west side of the lake with that on the east, this same method of reflection identification has proved to be quite accurate.

Fig. 9 shows the seismic map at the time of making the location for the first well. Although the map lacks completeness in the lake and on the west, nevertheless, it was felt that west closure was already suggested by the shape of the peripheral contours on this map. Later seismograph work and drilling has proved this assumption to be reasonable. Fig. 10 shows a map on a strong energy zone in the Tertiary. The slight nosing is the only indication of the Parentis structure.

Depth Prediction

The depth to the top of the second unconformity was predicted to be around 7,200 ft. Although no shows were encountered in the overlying section, the first well was drilled on to this depth where the top of the reservoir was found. Until a velocity survey was run in the well it looked like the seismograph had performed

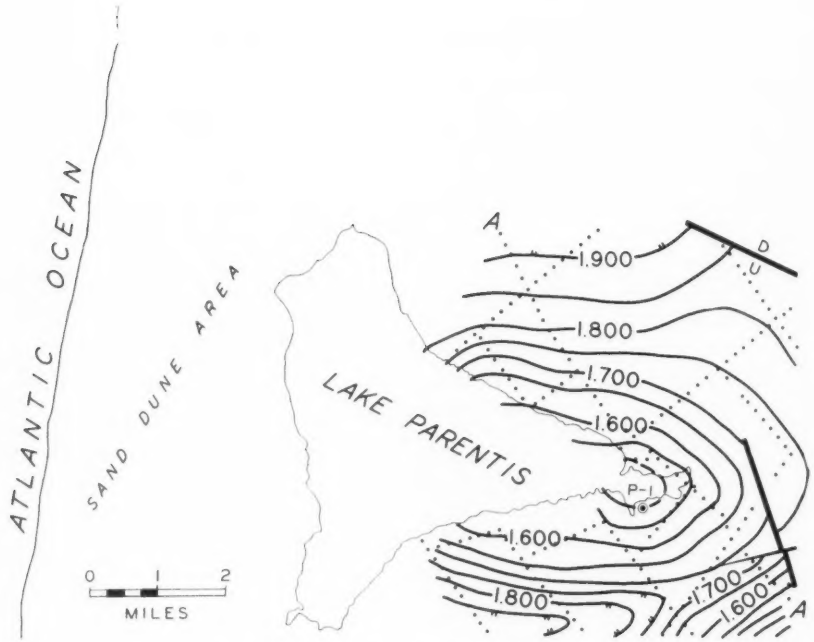

FIG. 9. First seismic map of the Parentis structure made on the top of the lower Cretaceous made in August, 1953.

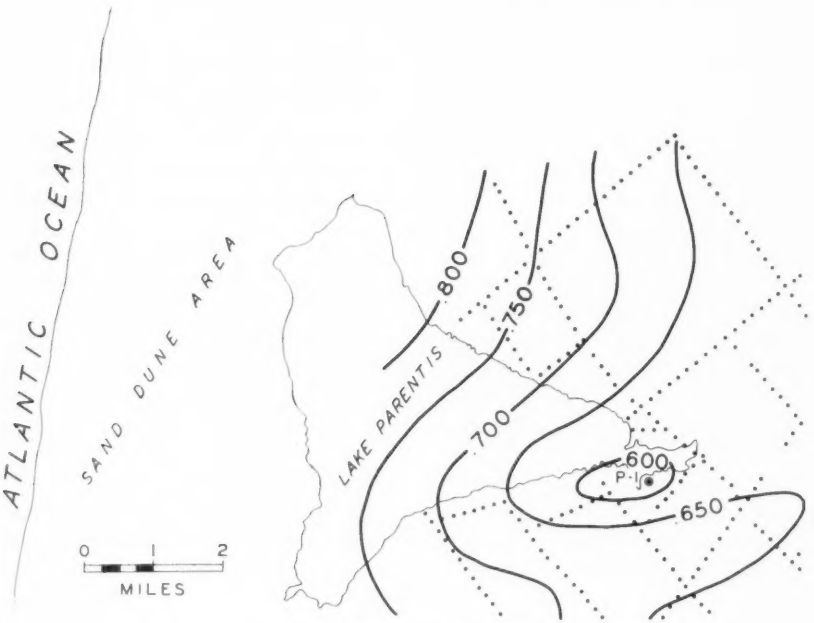

FIG. 10. Seismic map on a Tertiary horizon, August, 1953.

an amazing feat of predicting the depth to production. As it turned out, the velocities used were too high due to the abnormal thickness of the Tertiary and the mapped horizon was well above the producing zone. The seismograph interpretation, however, was the first to call attention to the unusual thickness of the younger beds that was actually encountered in the drilling of the discovery well.

Later Detailed Mapping

Fig. 11 shows the results of later detailed mapping. The map shows more control to the west, but leaves the main part of the Parentis structure unchanged. The synclinal area on the southeast is interpreted as a fault zone. On the first attempt at working the west side of the lake, the area seemed inaccessible. It lacked roads or trails and was irregularly covered with sand dunes. Through persistence this area was later mapped, but only after the discovery well was drilled.

THE PARENTIS FIELD

Production is mainly from a dolomitized zone in the basal part of a Lower Cretaceous limestone sequence (Fig. 12). The upper part of this sequence is not

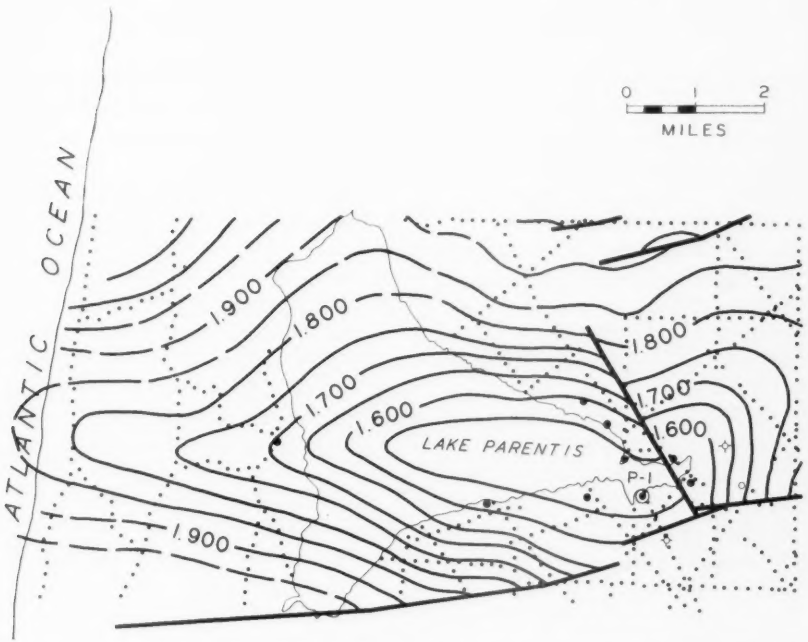

FIG. 11. Later detail seismic map on the top of the Lower Cretaceous made in May, 1955.

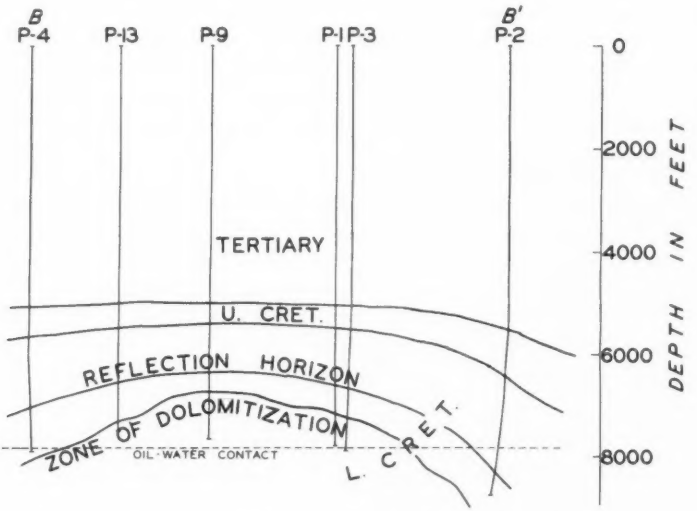

FIG. 12. Cross-section through the Parentis anticline, section *B-B'* in Fig. 13.

dolomitized. This is somewhat enigmatic as one would normally expect the dolomitization to be at the top of the series. It is irregular in its depth and degree of occurrence and is not related to any recognized unconformity within the limestone series.

Production has been established also in the upper dense part of this limestone section. It is fine grained with small nearly vertical fractures. Productive intervals within this zone are separated by shale or dense limestone streaks. The total productive interval in the upper zone varies from 266 to 754 ft. The lower zone, the dolomitized part, is highly vugular, cavernous and fractured, with individual productive units separated by dense compact dolomitic limestone or dolomite. The total thickness of the lower zone found above the water table varies from 0 to 600 ft.

Above the reservoir is a shale interval of about 1,000 ft. in thickness. This is also Lower Cretaceous in age. It is capped by an upper Cretaceous cherty limestone. Although this limestone has good porosity and well developed structural closure, it gives no hint of being productive. It is about 900–1,000 ft. thick.

Overlying the Cretaceous are about 5,000 ft. of Tertiary beds representing Eocene, Oligocene, Miocene, and Pliocene ages. No shows have been found in this section.

Fig. 13 is a subsurface map of the Parentis oil field contoured on the top of the reservoir. Since the axis of the structure lies in the middle of the lake, the actual shape and extension of the structure is not definitely known. It seems to be

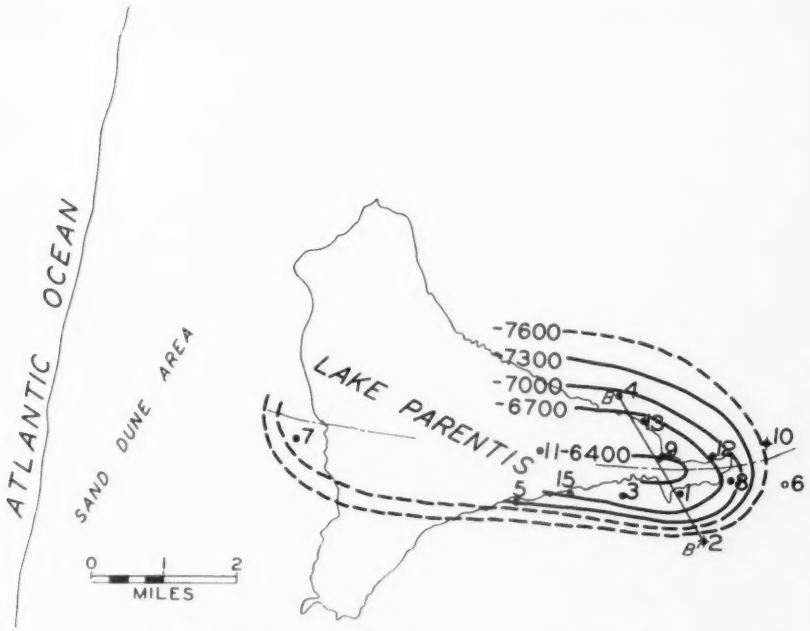

FIG. 13. The Parentis oil field. Structure map from well depths. Contours are on the top of the reservoir.

fitting the seismic picture reasonably well. Therefore, it is too early to give any reserve estimate. It appears certain, however, that Parentis is a major oil field.

It is currently producing 12,500 bbls. per day from 7 wells. This daily production will be increased as more wells are drilled in the lake.

Its importance as a discovery is magnified by its geographical location. It is the most important discovery in France and promises to be the biggest field discovered to date in western Europe.

ACKNOWLEDGMENTS

The writers are indebted to the Esso Standard, France, for permission to publish this paper and to the many employees of Esso Standard, France, whose accumulated efforts provided these data.

GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 828–838, 10 FIGS.

THE REFRACTION SEISMOGRAPH IN THE ALBERTA FOOTHILLS*

G. J. BLUNDUN†

ABSTRACT

In the Alberta foothills the most valuable use of the refraction seismograph is for the definition of overthrust faulting in the Mississippian limestone which is overlain by a faulted, overthrust, and overturned Cretaceous section. Normally, two refracted arrivals are recorded with characteristic interval velocities of 14,000 ft/sec and 21,000 ft/sec, the former arising from an unknown Cretaceous marker, and the latter from the Mississippian. In contrast to a shot-range of 65,000 ft required to record the refracted arrival from the Mississippian at a depth of 10,000 ft as the first event, a range of 20,000 ft permits recording it as the later event, with consequent improvement in the quality and reliability of the data, reduces the amount of surveying required together with smaller dynamite charges, and improves radio communication. A geophone spread of 6,300 ft with single geophones at 300 ft intervals recorded on 22 traces is recommended.

Both in-line and broadside refraction with the Mississippian arrival recorded as the later event have been used successfully with certain advantages to each method. The former permits continuous determination of the interval velocity of the refracted events as well as providing two-way control; the latter is considerably faster, and often faulting may be observed directly on the seismograms without reduction of the data. Specimen seismograms are included to illustrate the two methods.

Field operating conditions pertaining to survey tolerances, shot formation, size of dynamite charges, the weathering shot as a polarity check, filtering, geophone frequency, and costs are discussed.

INTRODUCTION

As illustrated in Fig. 1 the foothills area of Alberta, Canada, lies immediately to the east of the front range of the Rocky Mountains; the areas of current interest in these foothills are Pincher Creek, Savannah Creek, Turner Valley, Jumping Pound, and Brazeau.

The refraction seismograph is of the greatest significance for the definition of overthrust faulting in the Mississippian limestone of the Alberta foothills; secondarily, it provides data for the construction of a map of the Mississippian. One considerable disadvantage in its use is that only one, two at best, horizons may be mapped; further, it is costly. However, in conjunction with reasonably good velocity control, good refraction data can be very useful, and may be accurate to within less than $\pm$ 100 ft for depth measurement.

The topography undulates from deep valleys to high ridges, usually with a thick timber and brush cover which necessitates the clearing of lines by an axe crew or bulldozer before work may commence.

The sedimentary section overlying the Mississippian limestone series, as represented in Fig. 2, consists mainly of fissile shales, and hard, competent sandstones of Upper and Lower Cretaceous age, together with the Jurassic and Triassic beds. These shales and sandstones have been overthrust, faulted, and even

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† Oilwell Operators Limited, Calgary, Alberta, Canada, now known as the Home Oil Company.

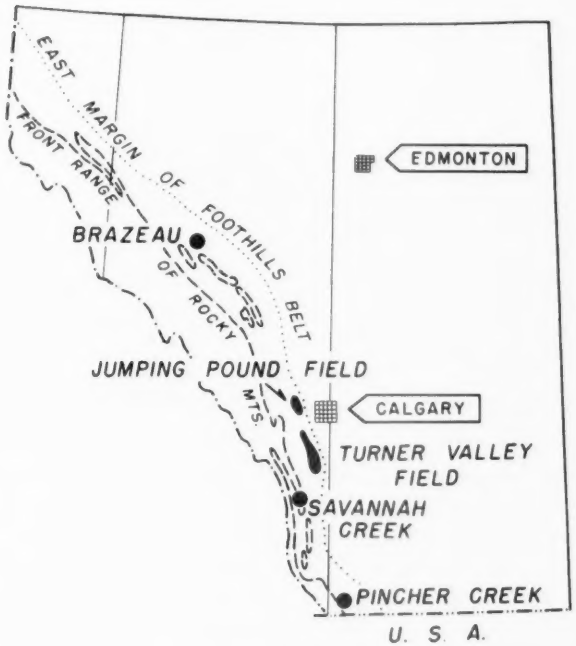

FIG. 1. Areas of current interest in the Alberta foothills (After T. A. Link).

overturned as a result of the movement in the Paleozoic. The eastward thrusting produced thrust blocks and slices in the limestone with horizontal displacements of the order of 3,000 ft. The Mississippian is found as shallow as 3,500 ft in Turner Valley, and as deep as 12,000 ft at Pincher Creek.

Be it the refraction or reflection seismograph in the Alberta foothills, the possible presence of high velocity material in the Cretaceous section which may introduce false evidence of structure in the Mississippian demands continuous vigilance.

Velocities have been measured in some wells in the localities of current interest in the foothills, but velocity data in the remainder is sparse. Generally, the average vertical velocity to the Mississippian is known to be 12,000 to 13,000 ft/sec; near-surface velocity for the reduction of surface elevations approximates 10,000 to 11,000 ft/sec.

SEQUENCE OF REFRACTED EVENTS

Reference to Fig. 3, which is a time-distance plot of the typical refracted arrivals obtained with the refraction seismograph in the southern Alberta foothills,

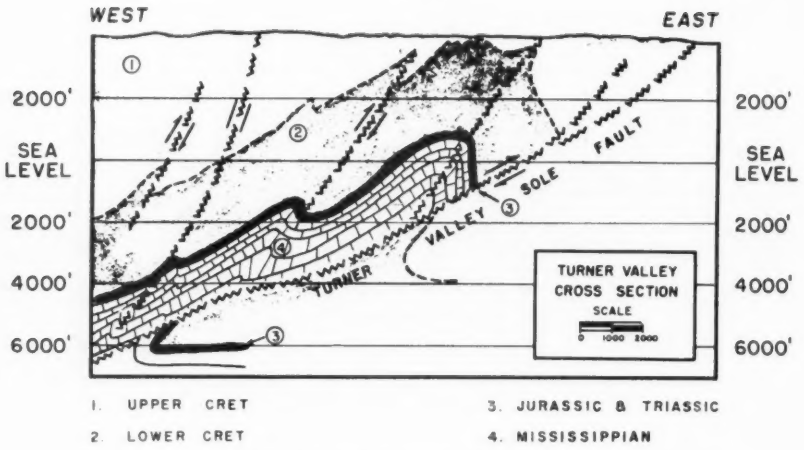

FIG. 2. Typical overthrust fault in the Mississippian limestone in this cross-section of the central Turner Valley area (After B. W. Gallup).

reveals that two events are recorded,—one with an apparent interval velocity of almost 14,000 ft/sec arising from an unknown Cretaceous marker which seldom persists with sufficient continuity to warrant mapping, and another with an apparent interval velocity of 21,000 ft/sec arising from the Mississippian at a known depth of 10,000 ft. In this example the critical distance, i.e. the distance from the shotpoint to the nearest geophone when the two events arrive simultaneously is 44,200 ft. If the refracted arrival from the Mississippian is to appear first on the seismogram, then the shot-range, i.e. shotpoint to geophone separation, will need be on the order of 60,000 to 65,000 ft. This practice is not recommended for the Alberta foothills because the total travel time of over 4 seconds through a very complex section is doubtful of accurate resolution, the survey distances involved are unwieldy, large charges of dynamite are necessary, the quality of the refracted events deteriorates, and difficulties in radio communication increase. If the refracted arrival from the Mississippian is to be recorded as the later event and to be separated by 0.3 to 0.4 seconds from the first, slower speed event for ease of reading, then the shot-range should be 20,000 to 35,000 ft, dependent upon the depth of the limestone. This is the practice recommended, which has none of the disadvantages noted in the alternate case.

The suggested geophone spread is one of 22 single geophones at intervals of 300 ft for 22 traces, to provide a spread length of 6,300 ft; usually, the smaller the geophone interval the better the quality of the refracted events. Care must be taken not to lengthen excessively the spread to be recorded from any single shotpoint, which would overweight the spread data as opposed to that determined at the shotpoint.

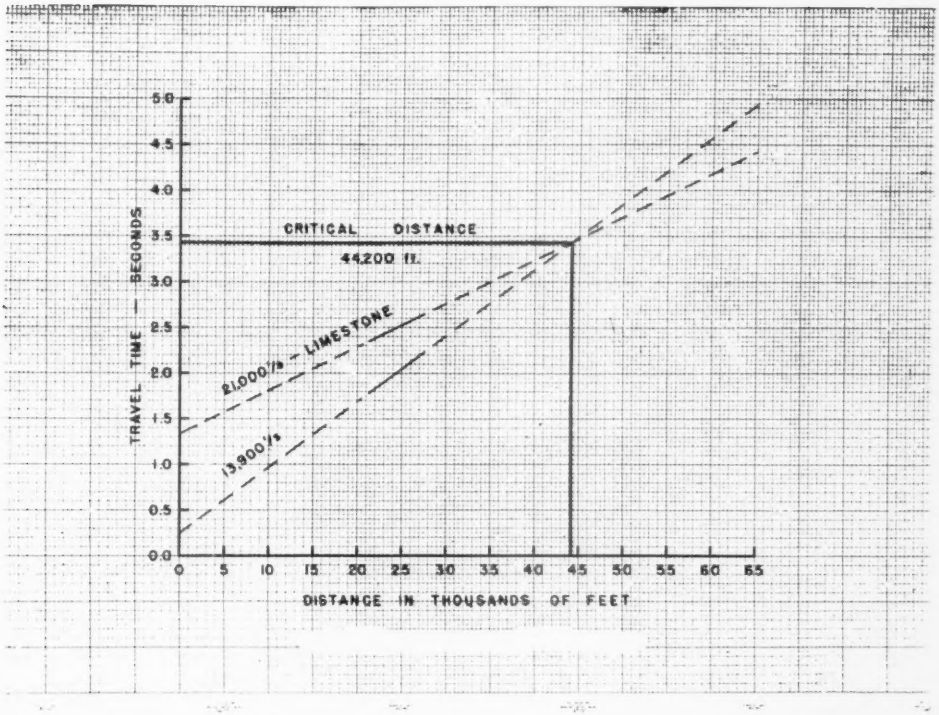

FIG. 3. Typical refracted arrivals in the Alberta foothills, from the Mississippian limestone at a depth of 10,000 ft.

IN-LINE REFRACTION

Fig. 4 illustrates a method of survey for geophone and shotpoint stations for in-line refraction, two way control, in which the station numbering is continuous, with the origin, 500+00, normally tied to a section corner. For ease of subsequent interpretation the geophone line should be straight. Each spread overlaps the next by two traces, i.e. traces 21 and 22 become traces 1 and 2, respectively, of the next spread. The shotpoints are numbered similarly to the spreads into which they are fired, with the direction indicated from shotpoint to spread, to provide two way control. Reverse control is obtained for pairs of spreads at coincident shotpoint-geophone stations, e.g. S.P. 1E and S.P. 9W. The separation of the shotpoint from each geophone is determined readily by subtraction.

Two in-line refraction seismograms, of comparable shot-range, are shown in Fig. 5, where the refracted arrival from the Mississippian at a depth of 9,000 ft is recorded as the later event. The change in separation between the two arrivals

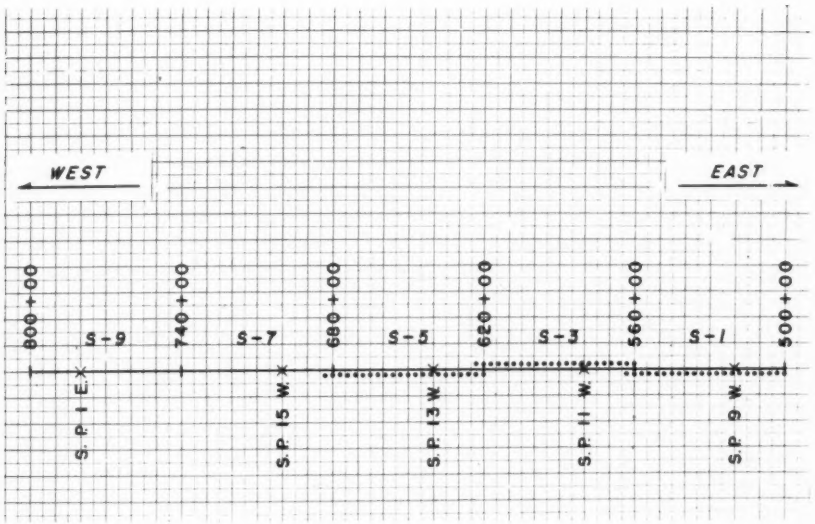

FIG. 4. Survey system for in-line refraction with two-trace overlap for successive geophone spreads, constant shot-range of 22,000 ft to provide two-way control and record the Mississippian refracted arrival as the second event.

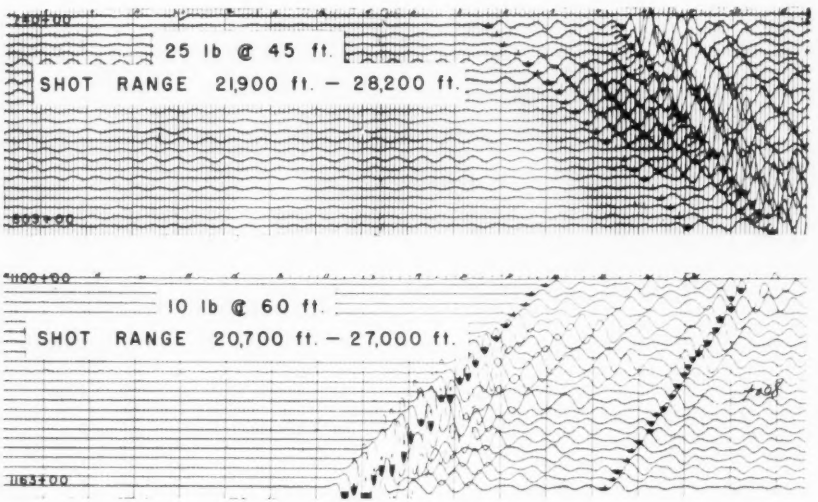

FIG. 5. Specimen seismograms of in-line refraction in which the second arrival is refracted from the Mississippian at a depth of 9,000 ft.

from the top to the bottom record is due to a fault in the Mississippian of throw of 2,200 ft that lies between the two different geophone spreads recorded in opposite directions on the same geophone line. The small charge of dynamite fired in each case is noteworthy.

Additional in-line refraction seismograms of 48 traces each, illustrated in Fig. 6, is an example of a practice to save holes and obviate reshooting, whereby 24 traces are recorded on high sensitivity, and 24 traces on low.

It is evident that the second refracted arrival on the bottom record arises from the drag fold or lip of the upper limb of a Mississippian overthrust fault lying at a depth of 12,000 ft. This phenomenon is seldom so clearly defined by the in-line refraction seismograph.

In-line refraction is recommended as the method to be used on the first line to be shot in any new area, preferably on strike, for accurate measurement of the interval velocities of the refracted arrivals, both over-all and locally,

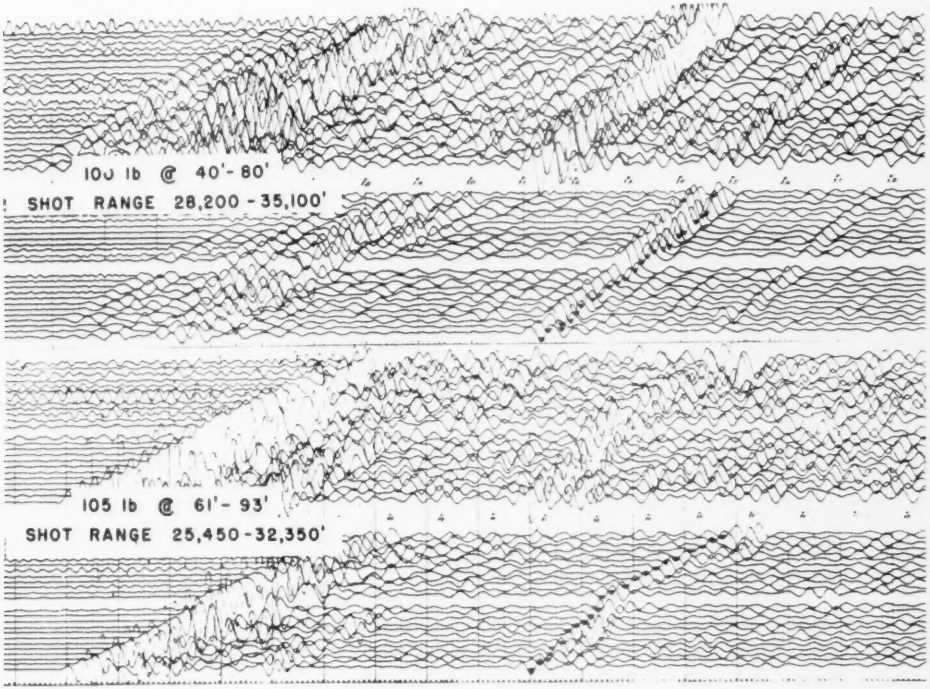

FIG. 6. Specimen seismograms of in-line refraction in which the second arrival is refracted from the Mississippian at a depth of 12,000 ft. Dual recording of 24 traces each on high and low sensitivity is used to save holes.

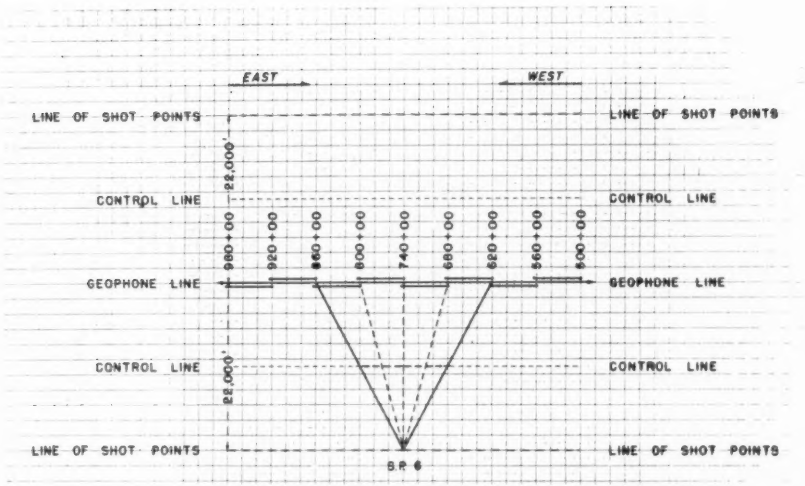

FIG. 7. Survey system for broadside refraction with two-trace overlap of successive geophone spreads, minimum shot-range of 22,000 ft to record the Mississippian refracted arrival as the second event.

from the two way control. However, to map the Mississippian lying at a depth of 8,000 ft, or greater, the length of the geophone line should be at least 12 to 15 miles to provide a sufficient and dependable number of depth control points. Faults defined and control data measured are assumed to lie in the same vertical plane as the shotpoint-geophone line.

BROADSIDE REFRACTION

The survey pattern of the geophone line and shotpoints for broadside refraction is represented in Fig. 7. The system of continuous station numbering, and spread distribution on a straight geophone line is similar to that for in-line refraction. However, the shotpoints are located on two lines parallel to, but separated from the geophone line by a distance determined from previous in-line refraction to provide the most suitable shot-range, 22,000 ft in this instance, which will maintain and identify the second refracted arrival as that from the Mississippian. The disposition of shotpoints along the shotpoint lines is a matter of preference, as is also the number of spreads to be recorded from any one shotpoint; the recommended spread coverage recorded from one shotpoint should not exceed 30,000 ft. If this should be exceeded the slant distance to the outside geophones may approach the critical distance previously referred to, and the two refracted arrivals approach one another to render the reading of either one difficult. Four spreads of 6,000 ft each for a total recorded geophone coverage of 24,000 ft is adequate. The resultant line of control data from broadside refraction lies halfway between the shotpoint and geophone line, and parallel to the latter.

Fig. 8 is a group of four seismograms from four consecutive spreads fired broadside from a single shotpoint, with minimum shot-range of 19,600 ft. The shotpoint is located opposite the centre of the group with the refracted arrival from the Mississippian recorded as the second event. At the centre of the group where the shot-range is the shortest, the separation between the two arrivals is the greatest; as the shot-range to the outer geophones increases toward the critical distance the amount of this separation decreases. Once again, the size of the dynamite charges is significantly small.

In Fig. 9 is shown another group of four broadside refraction records which were recorded in a similar manner, but in this instance define a Mississippian fault at 10,000 ft in depth with a throw of 2,000 ft by means of the second refracted arrival. An apology is offered for the poor photography on some of these records;

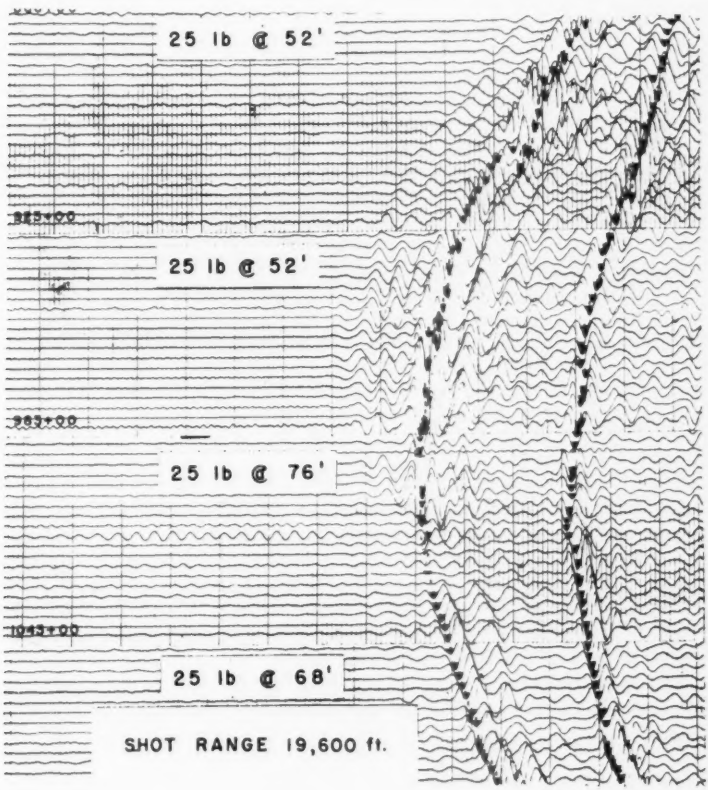

FIG. 8. Four specimen seismograms of broadside refraction recorded from four successive spreads out of one shotpoint at a minimum shot-range of 19,600 ft in which the second refracted arrival arises from the Mississippian at a depth of 9,000 ft.

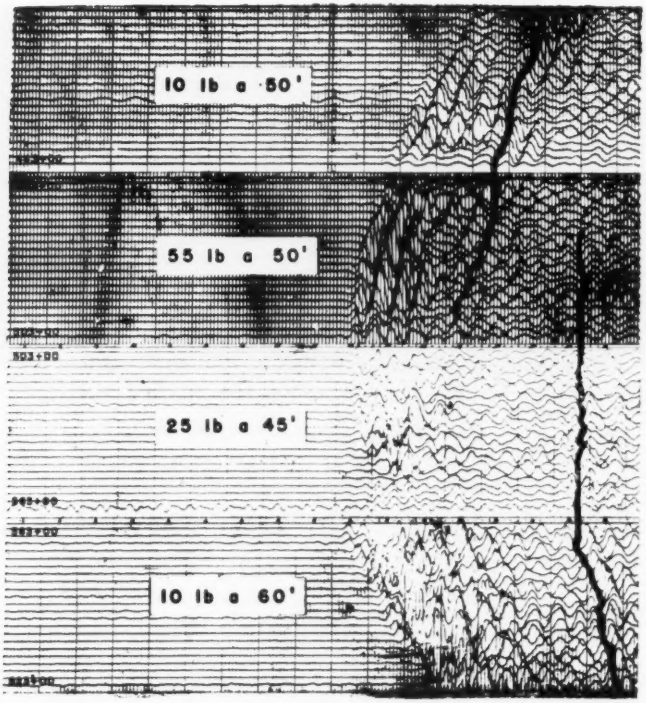

FIG. 9. Four specimen seismograms of broadside refraction recorded from four successive spreads out of one shotpoint at a minimum shot-range of 20,000 ft in which the second refracted arrival defines a fault in the Mississippian at a depth of 9,000 ft.

nevertheless, this is a good example of fault definition in the Mississippian by broadside refraction. The dynamite charges are relatively small.

The advantages of broadside refraction are:

(a) It is considerably faster than in-line refraction in that two lines of control data, one on each side of the geophone line, can be obtained simultaneously with a shooting truck on each side progressing from shotpoint to shotpoint as the spread progresses along the geophone line.

(b) Fault definition in the Mississippian may be observed directly on the records before reduction of the data to cross-section form, and permits location of the fault immediately; it is, therefore, of peculiar value on dip lines.

The disadvantages of broadside refraction are:

(a) The interval velocity of the refracted arrivals cannot be measured.

(b) Reverse and two way control is not provided.

Let there be no doubt as to the efficacy of the use of the broadside refraction seismograph; experience in the Alberta foothills has provided ties of the order of 100 ft, or better, with crossing lines, both broadside and in-line, together with wells drilled to the Mississippian.

OPERATING OBSERVATIONS

The quality of the refracted arrivals should be good enough to permit correlation from trace to trace, and record to record.

In survey a tolerance of $\pm$ 50 ft in a horizontal distance of 22,000 ft is permissible, while one of $\pm$ 10 ft in elevation is satisfactory. Government township plats which contain the distances in chains along the side of each section should be

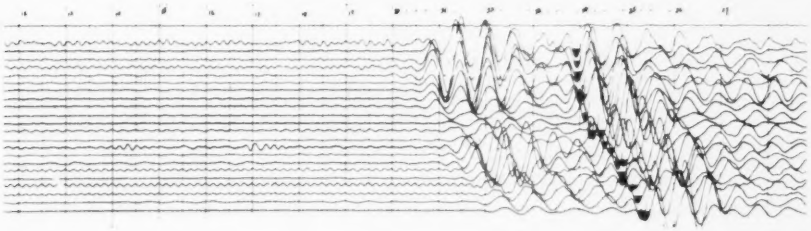

FIG. 10. Broadside refraction seismogram recorded at a shot-range of 21,600 ft with 5 lbs. of dynamite; the second arrival is from the Mississippian at a depth of 9,000 ft.

used to check the location of surveyed stations. Use of a transit is preferable to a plane table.

It has been observed that almost without exception the quality of the record obtained was dependent upon the formation in which the shot was fired. Clay and shale were the best. Sandstone, and, of course, gravel and sand were to be avoided. Possibly the commonest error is overshooting. Charges of 15 to 50 pounds with a shot-range of 20,000 ft and greater are usually ample. Fig. 10 is a seismogram taken at a shot-range of 21,600 ft with 5 pounds of dynamite.

Linemen will persist in reversing the polarity of geophones occasionally when connecting them to the cables. If the weathering shot on the spread is taken before any refraction records it will provide a check on polarity. Initial suppression should not be used. Automatic gain control with a normal time constant has been employed satisfactorily, with no filtering, although some filtering on the high side to reduce the effect of wind noise has not been harmful. A 26 conductor, portable cable, 6,300 ft long, split into four sections can be readily carried on breast reels together with 22 geophones. Slack of 5 ft was found to be adequate between geophone outlets at 300 ft intervals to cope with surface elevation changes of as much as 300 ft within the spread.

The period of the refracted arrivals in the Alberta foothills is from .040 to

.050 seconds, and has been satisfactorily recorded using geophones of frequency 6 to 10 cps. On many days it may be necessary to bury geophones to reduce wind noise, or even to start shooting at daybreak and shut down at noon when the wind velocity is high. In the winter the snow cover has a beneficial effect in reducing noise from wind when geophones are dug into the bottom of the snow and onto the frozen ground.

All radio transmitters must be licensed by the Federal Department of Transport to operate on the geophysical frequency of 1652 kc. Power of 30 watts is adequate.

In bush covered foothills two refraction spreads a day is normal practice. Seldom are three exceeded in the best of conditions.

Operational costs per 208 hour crew month approximates $23,000 for recording, drilling, and bulldozing.

Because there are numerous publications dealing with refraction interpretation, Gardner (1939), Dix (1952), Dobrin (1952), and Nettleton (1940), to name only a few, the subject has been omitted deliberately in this paper.

ACKNOWLEDGMENT

The author wishes to thank the Texaco Exploration Company and Oilwell Operators Limited for their assistance, and permission to publish copies of refraction seismograms together with other material.

GEOPHYSICS, VOL. XXI, NO. 3 (JULY, 1956), PP. 839–853, 7 FIGS.

GEOPHYSICAL STUDIES IN THE INTERMONTANE BASINS IN SOUTHERN CALIFORNIA*

DON R. MABEY†

ABSTRACT

Geophysical surveys were made by the U. S. Geological Survey in Searles Lake basin and in the Mojave Desert near Barstow, California to test the application of geophysical exploration to the study of the geologic problems associated with the intermontane basins of southern California. In Searles Lake basin a coordinated gravity and seismic reflection and refraction survey indicated that the fill in the basin is about 3,300 feet thick with the greatest thickness occurring east of the center of the basin. The regional gravity data from the area near Barstow can be used to estimate the thickness and extent of the Tertiary and Quaternary deposits.

INTRODUCTION

The Garlock fault separates regions of greatly differing surface and structural features. The area north of the Garlock fault (Fig. 1) is characterized by north-trending ranges and intervening basins of interior drainage. Some of the ranges are apparently fault blocks, and some of the basins are fault-bounded troughs; however, the geologic structure is complex, with adjacent blocks often having distinctly different geologic history. The geologic section is also complex and includes rocks ranging in age from early Precambrian to Recent. During parts of the Cenozoic era fluviatile and lacustrine deposits were deposited in separate basins (Jahns, 1954).

South of the Garlock fault the western Mojave Desert, which lies in the wedge between the Garlock and San Andreas faults, is generally characterized by hills with no definite trend surrounded by large alluvium-covered closed basins. The region is underlain by a pre-Tertiary "basement complex" composed largely of plutonic igneous rocks enclosing pendants of metasedimentary and metavolcanic rocks. The basement complex is overlain in places by nonmarine sedimentary, pyroclastic, and volcanic rocks of Tertiary age deposited in local basins. The Tertiary rocks are locally deformed and cut by volcanic intrusions. The pre-Tertiary and Tertiary rocks are overlain unconformably by alluvial sediments of Quaternary age which cover nearly all the valley areas.

In addition to the academic interest in the geology of this region of southern California there are several economic interests the key to which is an understanding of the deposition of the Cenozoic sediments. Among the most important mineral resources of the region are the saline deposits in the Cenozoic sediments. The systematic search for additional saline deposits, such as those presently being developed at Searles Lake and at Boron, is dependent upon a knowledge of the

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present disposition of the Cenozoic sediments and an understanding of the basins in which these sediments were deposited. Before an adequate evaluation of the petroleum possibilities of the Cenozoic section can be made, a knowledge of the depth, extent, and structure of the Cenozoic basins is necessary. Of critical importance, particularly in the Mojave Desert, is the development of the ground water resources to supply the agricultural developments and the expanding mili-

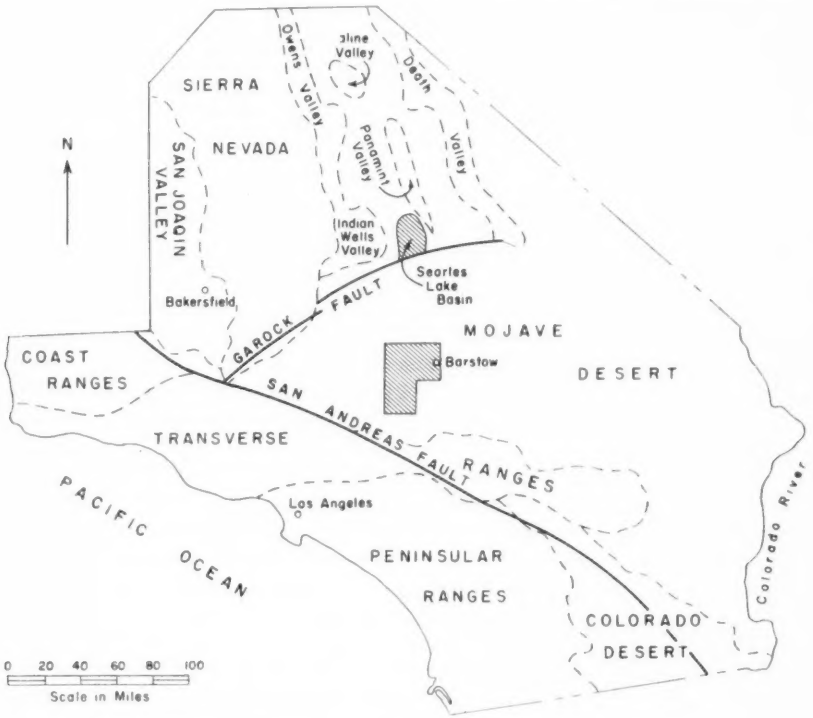

FIG. 1. Index map of southern California showing location of geophysical surveys.

tary and industrial installations with their associated population growth. The region is largely dependent on the ground water stored in deep alluvium-filled valleys. As the precipitation is generally meager, these reserves are sustained from run-off originating in the mountain areas in and surrounding the desert. So that the ground water resources may be fully developed, it is necessary to locate the buried channels through which the recharge water moves, and also to locate the areas of fill where the water is stored.

Some method of obtaining subsurface information in the areas of Cenozoic

fill is essential to an understanding of the geology of the intermontane basins. This is particularly important because of the cover of Quaternary deposits which imposes serious limitations on the information that can be obtained from surface geologic mapping alone. Geophysical exploration on a scale large enough to reveal the broader features of the Cenozoic geology is logically the first step in obtaining subsurface information. After geophysical surveys have indicated the major features, core drilling can be used to provide more direct information and provide control for a more detailed interpretation of the geophysical data.

In 1953 the U. S. Geological Survey made a series of investigations to determine what methods of geophysical exploration are applicable to the study of intermontane basins of southern California. Seismic reflection and refraction, ground and airborne magnetic, and gravity methods were tested under a variety of conditions. Because of the density contrast between the Cenozoic sediments and pre-Cenozoic rocks, gravity observations were found to yield the most consistently useful data in studying the problems relating to the intermontane basins. In local areas, notably Searles Lake basin and Panamint Valley, seismic methods produced pertinent information. In the western Mojave Desert the heterogeneous nature of the Cenozoic fill limits the usefulness of seismic methods; however, some fault traces can be located by refraction profiling. The magnetic observations give some information on the nature of the basin fill but most of the magnetic anomalies seem to reflect intrabasement features that have not been directly related to the study of the Cenozoic basins.

The application of geophysical exploration to the problems of the intermontane basins of southern California can be illustrated by a discussion of the gravity and seismic data collected in the Searles Lake basin and the gravity data collected in the Mojave Desert near Barstow.

INVESTIGATIONS AT SEARLES LAKE

The primary purpose of the geophysical work in Searles Lake basin was to determine the configuration of the bedrock under the basin fill. A secondary purpose was to obtain information concerning the stratigraphy and structure of the fill within the basin, particularly with regard to determining the lateral limits of the known saline deposits and detecting any additional deposits that might be present.

Searles Lake basin (Fig. 2) is about 25 miles north-south by 10 miles east-west. The basin is bounded on the east by the Slate Range and on the west by the Argus Range; to the north the basin is terminated by a junction of the two ranges; the trace of the Garlock fault approximates the southern boundary of the basin. Though the north-south trend of Searles Lake basin is typical of the Basin and Range province, the basin is smaller than most of the others in the region. There is direct and indirect surface evidence of faulting, but there is no conclusive surface evidence indicating whether the basin is primarily a structural or an erosional feature.

At least one deep lake has filled the basin to a level of about 640 feet above the present basin floor (1,616 feet). The maximum water level is determined by a pass at the southeastern corner of the basin through which the water overflowed into Panamint Valley (Gale, 1914). Large alluvial fans extend out into the basin

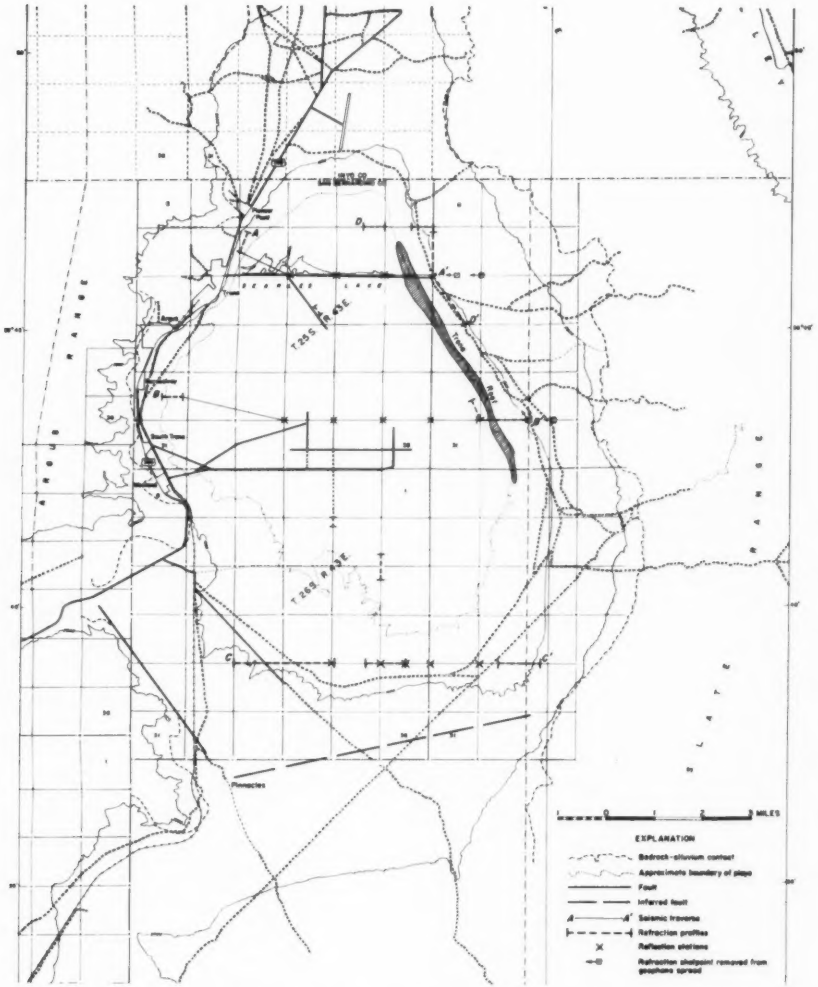

FIG. 2. Searles Lake, showing certain geologic features and location of seismic stations and traverses.

from the front of the Slate Range, and smaller fans occur along the front of the Argus Range. The Slate Range is composed primarily of pre-Tertiary sedimentary and metamorphic rocks, and the Argus Range is composed mostly of intrusive rocks.

Searles Lake, situated near the center of the basin, is unique among the playas of the region because of the variety of saline minerals contained in the lake sediments. Although much of the playa surface is very soft and the water table is at or near the surface, there is water on only small areas of the surface under normal conditions. Near the center of the playa the uppermost of two major salt bodies is exposed. Where the salt is exposed there is a compact surface crust about two feet thick. Below this crust the salt body is composed of well developed crystals and has a high porosity. Saturated brine filling the pore space is pumped from selected areas and processed in the chemical plants.

The upper salt body is lenticular and has a maximum thickness of about 90 feet. Away from the exposed center the salt is buried under lake muds, and as a result the lateral limits of the subsurface salt cannot be determined from surface indications. The lower salt body is smaller than the upper body and is separated from it by 12 to 20 feet of lake mud. Many holes have been drilled into and through the two salt bodies, but few holes have been drilled much below the base of the lower body, and no hole on the playa has been drilled to bedrock.

Along the east and northeast edge of the playa zone is a feature known as the "trona reef." This reef, which rises a few inches above the playa surface, is a saline efflorescence composed mostly of the hydrated sodium acid carbonate, trona, and apparently is the product of the evaporation of trona-bearing waters rising to the surface. Why the waters rise in this linear area has been a matter of conjecture.

In the vicinity of the Searles Lake playa, 185 gravity stations were established over an area of about 80 square miles. The gravity coverage was extended onto the bedrock outcrops in the bordering mountains to obtain a background for interpreting the data over the basin floor. Gravity stations were established using a Worden gravimeter at bench marks and section markers. The elevations at the section markers were determined by level and transit surveying. All elevations are accurate to within 2 feet. The observed gravity values are considered accurate to within 0.2 milligal.

The gravity was reduced to an arbitrary gravity datum and corrected for the effects of elevation, latitude, and terrain (through zone K on the Hammer chart) (Hammer, 1939). In making the elevation correction, a factor of 0.063 milligal per foot was used. This corresponds to a density of 2.43 gm/cm^3 which is thought to be about the bulk density of the alluvial fan material over which the greatest number of important elevation variations occur.

The dominant gravity feature in Searles Lake basin is a large gravity low elongated in the north-south direction centered east of the present center of the basin. This is shown in Fig. 3, the Bouguer anomaly contour map with a one-

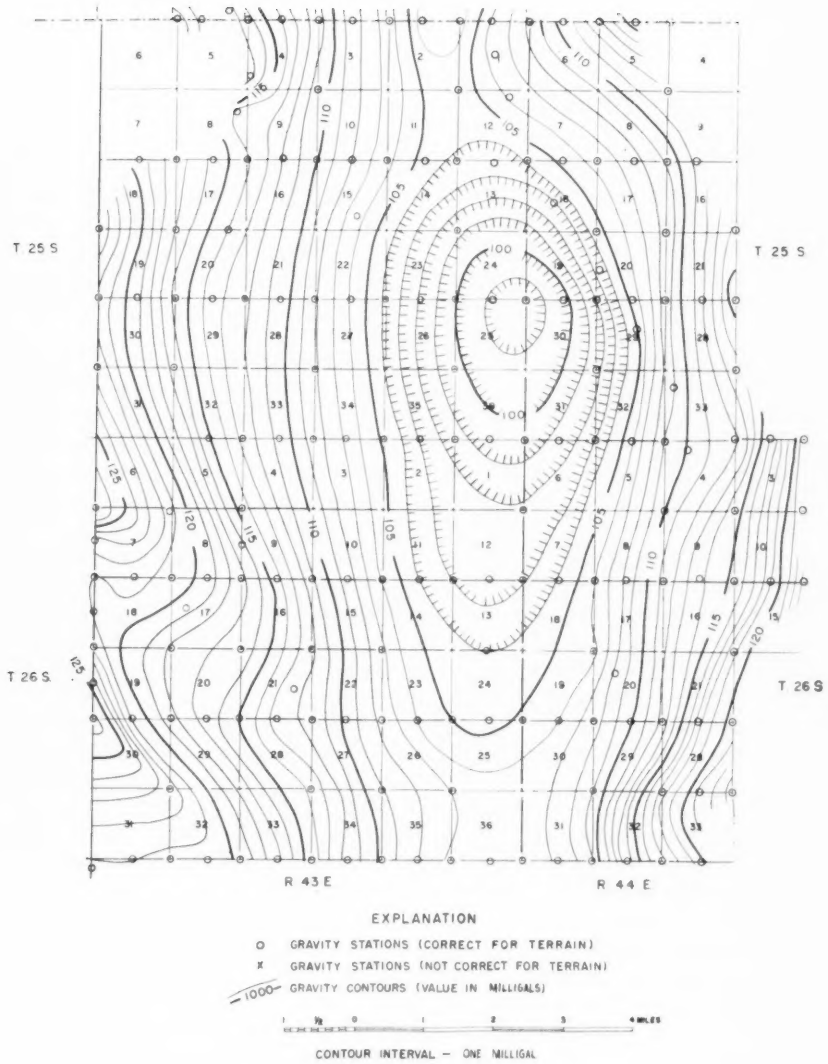

FIG. 3. Searles Lake gravity anomaly map.

milligal contour interval. The gravity minimum along the east edge of the playa is about 20 milligals less than gravity values on bedrock in the mountains on each side of the basin. The position of the low indicates that the fill in the basin is asymmetrical with the thickest section of fill occurring to the east of the center of the basin. Although it is apparent that the bedrock rises more abruptly to the east than to the west from the low point in the basin, there is no conclusive evidence of a major fault along the east side of the basin. The tightening of the gravity contours in the central part of T. 26 S., R. 44 E., indicates that the bedrock surface rises more abruptly in this area and may indicate the presence of a northeast-trending fault. Southwest of the playa there is gravity expression of a northwest-trending fault that has been mapped from surface evidence.

Seismic tests were made over the salt bodies to ascertain if it is possible to determine the lateral limits of the salt. Observations were made on three lines across the playa to determine the depth to bedrock with refraction shooting being used for shallow depths and correlation reflection shooting for greater depths. For the seismic studies a 12-channel refraction seismograph and a 12-channel reflection seismograph were used. Shot holes were drilled to depths of from 15 to 30 feet with a power auger mounted on a truck. Refraction profiles covering about 9 traverse miles, with spreads ranging from 120 feet to 19,000 feet, were obtained. Reflections were recorded at 12 stations. The location of the seismic profiles and stations is shown in Fig. 2.

The shallow refraction tests over the salt body indicated that this method is not applicable to determining the lateral limits of the salt, at least along the south edge of the body where the tests were made. Computations made by conventional methods from the refraction records indicated the depth and dip of the bedrock surface to depths of 2,000 feet, where no near surface high velocity layers are present. In the deep parts of the basin the quality of the bedrock reflections varied from no reflections in the east to good reflections near the center of the present playa. The refraction and reflection data agreed satisfactorily in the western part of the basin. On some of the records in the deeper parts of the basin, more than one reflection was recorded. Where this occurred, the bedrock reflection was correlated on the basis of character and a projection of the computed dip. The additional reflections, with one exception, seemed to come from horizons within the basin fill.

Velocity tests made on the salt outcrop indicated a velocity of 10,000 fps for the surface salt. Where the salt was covered by about 30 feet of mud a test indicated a velocity of 7,700 fps for the salt body. The depth to the salt computed from the travel time curves agreed closely with the depth recorded in a well log. Nearer the south edge of the salt body the velocity of the salt body had decreased to 5,300 fps. This velocity is about the same as was recorded for lake muds at similar depths where the salt is not present. As the velocity of the salt body decreases toward this edge until it is approximately that of the lake muds

at equivalent depths, the seismic refraction method could not be used, at least along this edge, to determine the lateral limits of the salt.

The velocity of 10,000 fps recorded on the salt outcrop probably indicates only the velocity of the compact crust. Where the salt body is covered by mud there is no crust and the velocity of 7,700 fps is the velocity of the porous salt body. The decrease in velocity toward the edges of the salt body is probably the result of an increased mud content.

The line *CC'* (Fig. 2) across the southern portion of the lake did not cross any known salt deposits. Refraction profiles indicate a low-velocity layer three or four feet thick at the surface; the base of this layer is the water table. Below this is a 50 to 120 feet thick layer in which velocity is 4,800 to 5,500 fps, and a layer 150 to 200 feet thick in which the velocity ranges from 5,600 to 6,100 fps. These layers are underlain by a layer with an indicated velocity ranging from 7,100 to 8,000 fps. The increase in velocity of this layer to the east will be discussed later. No further velocity increases above the basement were apparent from the travel time curves. Depths to the basement ranged from 600 to 2,700 feet.

No velocity increase resulting from compaction with depth is noted in the third major layer as might be expected, even though refraction profiles were shot where the layer has an apparent thickness of 1,500 feet. The absence of any velocity increase may indicate that the horizon mapped by the refraction survey is in reality a relatively thin layer that is underlain by lower velocity materials. If this is so, all the depth computations made from the refraction travel time curves will be too great. Computed reflection depths will also be too great as the reflection times were converted to depths using the velocities obtained from the refraction travel time curves.

As the traverses *AA'* and *BB'* were in part across the salt body which represents a near surface high-velocity layer, the refraction data were not nearly as complete along these lines as along *CC'*. Good reflections were recorded at stations located on the salt body. No definite reflections were recorded at the east end of either of the lines. Basement velocities were not apparent on the longest refraction profile that could be used in the area. A maximum velocity of about 9,500 fps was observed for the seismic layer which was increasing in velocity toward the east along the southern line. Few test holes have been drilled to the depth of this high-velocity layer (250 to 300 feet), but one hole, the log of which has been published by Smith and Pratt (1955), entered beds of trona at about 250 feet after going through a predominantly mud section below the lower salt body.

Where the center traverse crossed the area of the trona reef, the refraction travel time curves indicated a vertical velocity discontinuity. This discontinuity seems to be a fault along which the 9,500 fps velocity layer is displaced about 40 feet up to the east. This fault may control the linear area along which the trona-bearing waters rise to the surface to form the trona reef.

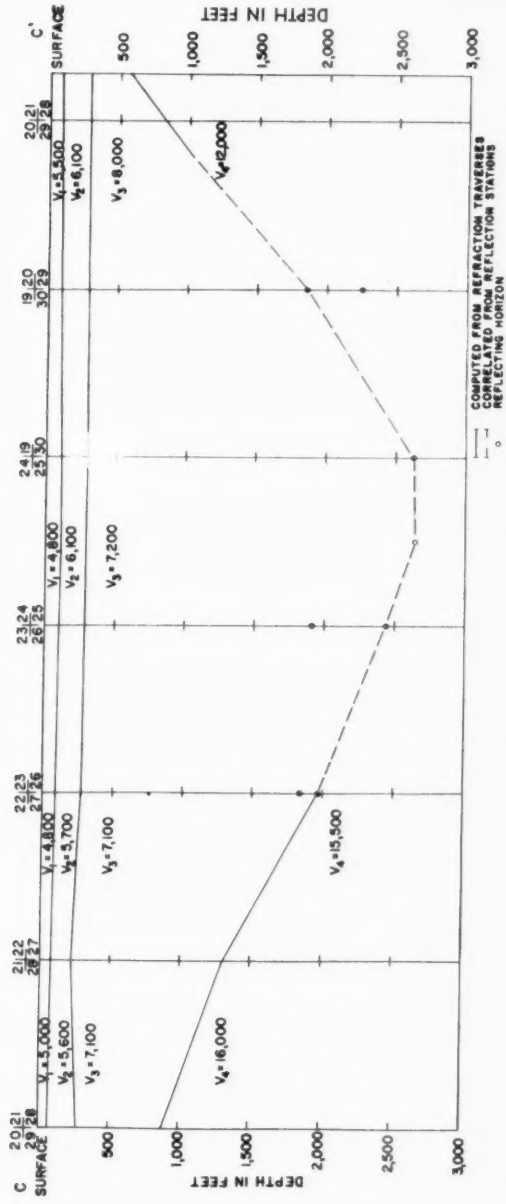

FIG. 4. Seismic results along line *CC'* Searles Lake.

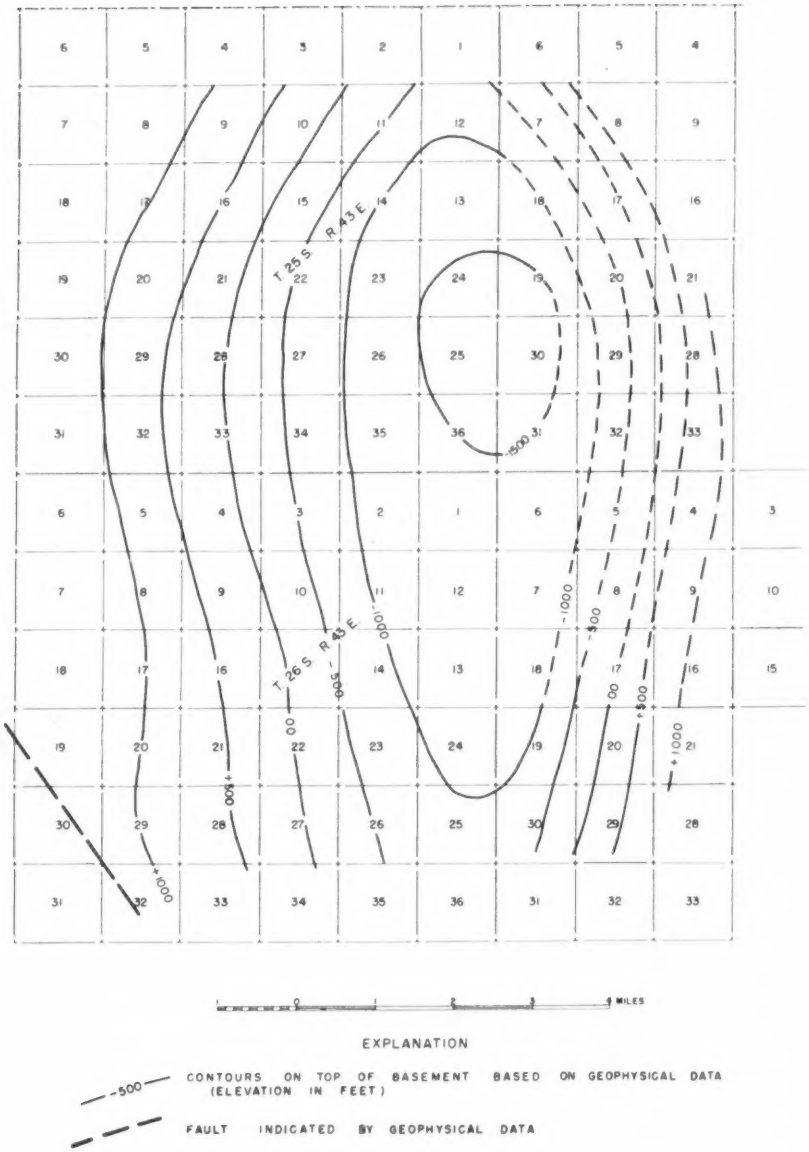
T 25 S R 43 E
T 26 S R 43 E
-500
-1000
+500
+1000
0 1 2 3 4 MILES
EXPLANATION
-500 CONTOURS ON TOP OF BASEMENT BASED ON GEOPHYSICAL DATA (ELEVATION IN FEET)
FAULT INDICATED BY GEOPHYSICAL DATA

FIG. 5. Contour map on top of basement rock at Searles Lake as calculated from geophysical data.

Using both the gravity and the seismic data it is possible to infer a configuration of the basement over all of the surveyed area. A contour map showing the generalized basement surface as inferred from the geophysical data is illustrated in Fig. 5. In constructing the contour map the seismic data were used for control where they were available and the gravity data were used in other areas.

In Fig. 6 a section across the basin corresponding approximately to the location of seismic traverse *BB'* is shown. The assumed bedrock surface is based on both seismic and gravity data, and the observed gravity is plotted with no attempt to remove any regional variation that may be present. The theoretical

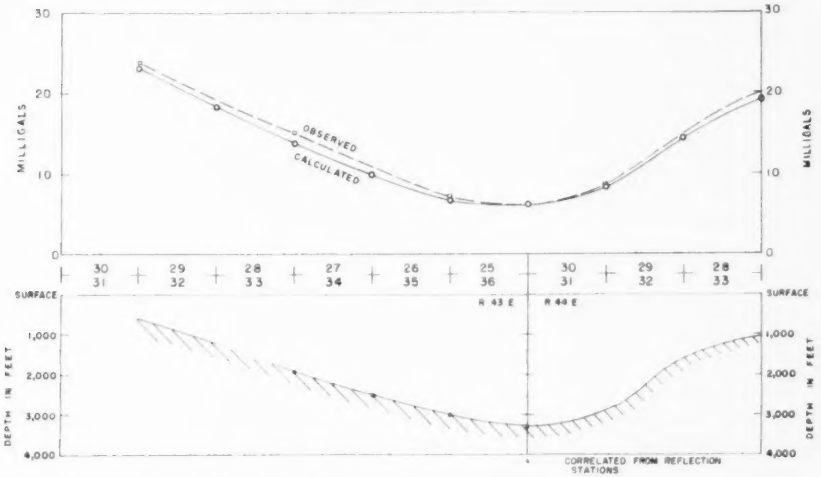

FIG. 6. Comparison of theoretical and observed gravity anomalies along line *BB'* Searles Lake.

gravity anomaly calculated by using a two-dimensional graticule and the assumed bedrock profile is also illustrated. A density contrast of 0.65 between the basement rock and the basin fill was assumed without any attempt to consider density increases due to compaction with depth. The agreement between the observed and calculated anomalies indicates that there is a density contrast of 0.6 to 0.7 between the basin fill and basement rock.

INVESTIGATIONS NEAR BARSTOW

The general geology of the north and west portions of the Barstow quadrangle is typical of the western Mojave Desert. The relief is moderate, totaling about 1,200 feet. The more prominent topographic highs such as the Kramer Hills, Shadow Mountains, and Iron Mountain, have a core of pre-Tertiary basement rocks. The most extensive outcrop of Tertiary sediments occurs in the vicinity of the Kramer Hills where several thousand feet of section is exposed. The valley

areas are covered with Quaternary alluvium. The Mojave River, which begins in the San Bernardino Mountains and crosses the Barstow quadrangle, is the largest single source of recharge water in the Mojave Desert.

A total of 223 gravity stations were established over about 650 square miles in the north and west portions of the Barstow quadrangle. Eighty-one of the stations were set at points where the horizontal and vertical control had previously been established by U. S. Geological Survey, U. S. Coast and Geodetic Survey, and the Army Corps of Engineers. The control for the remaining stations was established by plane table and transit surveys of the gravity crew. All elevations are accurate to within 4 feet. The gravity measurements were made using a Frost and a Worden gravity meter, and the observed gravity values are accurate to within 0.2 milligal.

The gravity data were corrected for latitude and elevation effects and reduced to an arbitrary gravity datum. An elevation correction factor of 0.06 milligals per foot was used. The magnitude of the variation of the terrain effect within the quadrangle is not of sufficient size to be important when the major anomalies are being considered; therefore, the correction for terrain effect has not been applied.

The simple Bouguer anomaly values show 38 milligals of relief over the area of the survey. Gravity highs occur over all the major basement outcrops. A major gravity low with two separate closures circles the Kramer Hills to the east and south. Another major low trending north is centered near Adelanto. An inspection of the gravity anomalies will reveal the general configuration of the basement surface; however, variations in the density of the Tertiary and Quaternary fill from one local basin to another and perhaps within individual basins introduce serious complications in the determination of the depth of fill without some direct control. An analysis of the gravity anomalies relative to the few deep drill holes in the western Mojave Desert indicates that no single density contrast between the Cenozoic and pre-Cenozoic rocks is applicable for making quantitative interpretation. Errors of several hundred percent may result from the use of incorrect density contrasts in any quantitative depth estimate where no direct control is available. Because adequate direct control is not generally available for making detailed quantitative interpretations over the basin areas, a simple order-of-magnitude depth estimate seems to be all that is justified for many of the anomalies.

Although gravity highs relative to adjoining basin areas occur over all major basement outcrops, the Bouguer anomaly values show large variations on basement outcrops in different parts of the region. As these variations cannot be accounted for by the density contrast between the Cenozoic rocks and basement rocks, nor from effects resulting from assumptions made in reducing the data, the variations must reflect intrabasement features. No explanation of these anomalies will be attempted here; however, it has been found that these anomalies

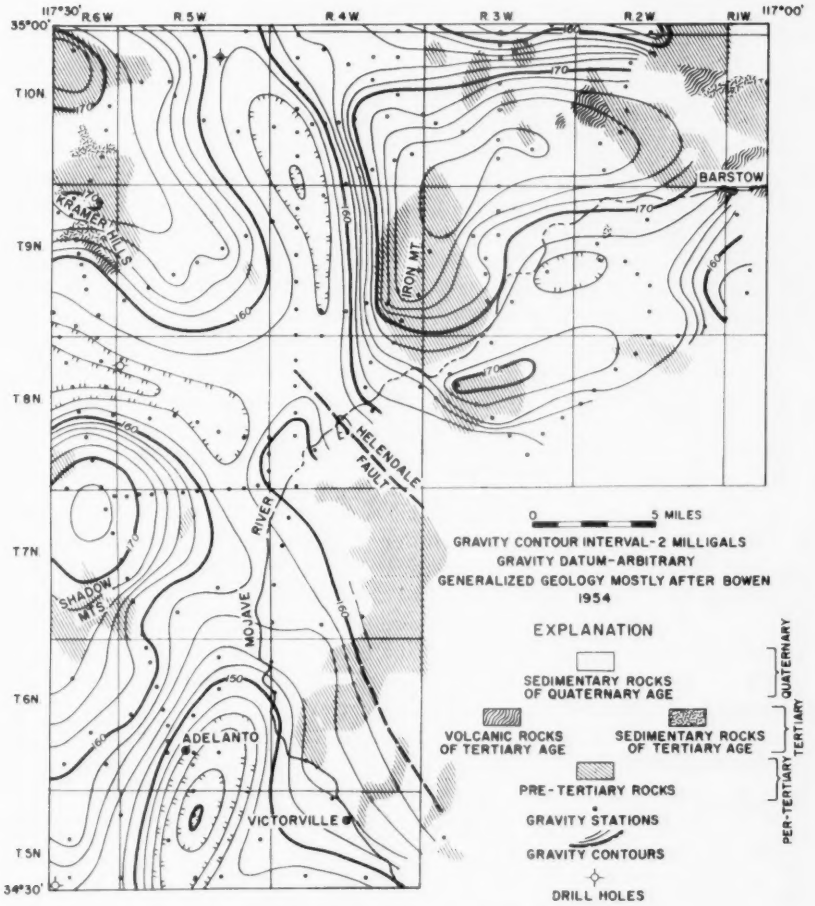

FIG. 7. Generalized geology and gravity anomaly map of part of the Barstow quadrangle, California.

are generally of such broad areal extent that they can be distinguished from anomalies associated with the Tertiary and Quaternary fills.

A contour map of the simple Bouguer anomalies with a 2-milligal contour interval along with the simplified geology is shown in Fig. 7. The north-trending gravity low between the Kramer Hills and Iron Mountain seems to be controlled on the east by a fault of considerable vertical displacement. The trend of this

inferred fault differs from the northwest-trending, strike-slip fault system which is considered to be dominant in the area. Because the vertical displacement along these faults is not always in the same direction, they cannot always be traced by their gravity expression. One of these faults, the Helendale fault (Bowen, 1954), extends tens of miles southeast from the southern end of this low. Another, the Lockhart fault, mapped just north of the quadrangle border, extends tens of miles northwest from the northern end of the low (Hewitt, 1954). The gravity data indicate that the Lockhart fault, or a branch of it, may join the indicated fault along the east edge of the gravity low. However, there is also indirect surface evidence indicating that the Lockhart fault extends southeastward toward Hinkley Valley, and the gravity data does not preclude this possibility. The inferred fault along the east edge of the low may be related to either or both the Helendale and Lockhart faults.

Granite was reported at 2,640 feet in a hole drilled as a test for oil on the north end of this low in sec. 11, T. 10 N., R. 5 W. (Bowen, 1954). If this report is correct, then the maximum depth to the basement in the area of this low is probably just east of the center of the low and in the order of 4,000 to 5,000 feet.

South of the Kramer Hills is an east-trending gravity low separating the Kramer Hills and the Shadow Mountains. Recently a 4,130-foot hole, which did not reach the basement, was drilled north of the axis of this low (T. W. Dibblee, personal communication). The hole bottomed in granite cobble conglomerate and sandstone, and it seems that this may be near the base of the fill. On the other hand this well did not penetrate, and possibly did not reach the 1,000-foot thick section of Tertiary volcanic flows and lake beds that overly the basement complex in the Kramer Hills four miles north, and thereby may have been bottomed more than 1,000 feet above the basement complex.

Southeast of the Shadow Mountains, in the vicinity of Adelanto, there is a north-trending gravity low. In the only important drill hole in the area, southwest of the anomaly, crystalline rock was reported at 1,340 feet (Bowen, 1954). The maximum depth of fill in the center of this low appears to be of the order of 5,000 feet.

The small gravity low north of the Kramer Hills is associated with a small basin area centered to the west of the quadrangle border. The gravity low south of Barstow may represent a westward extension of the Daggett basin, which has been mapped east of the Barstow quadrangle.

CONCLUSIONS

In Searles Lake basin a coordinated gravity and seismic reflection and refraction survey indicated the general configuration of the bedrock. Seismic refraction data indicated several velocity horizons and may prove useful in studying the stratigraphy of the basin fill. In the Barstow quadrangle the gravity data indicated the location, extent, and order of magnitude of thickness of the major deposits of Tertiary and Quaternary sediments.

In the basins of the Basin and Range province north of the Garlock fault gravity measurements will indicate the general configuration of the bedrock under the basin fill, and will generally indicate the relationship of the basin to the adjoining mountains. The success with which seismic methods can be used in the Basin and Range province is dependent upon the nature of the fill material, and thus varies from one basin to another. In some places both reflection and refraction methods will yield information on the thickness, stratigraphy, and structure of basin fill.

In the Mojave Desert the density contrasts between the Tertiary and Quaternary rocks and the pre-Tertiary rocks produce large gravity anomalies which can be detected by regional gravity surveys. These anomalies, although superimposed upon intrabasement anomalies, can be interpreted in terms of the approximate thickness of the Tertiary and Quaternary fill in the region. The information obtained from the regional gravity data is important in evaluating the possibilities of petroleum deposits existing in the region, and also in the search for buried saline deposits. Gravity measurements may prove to be of value in studying the occurrence and movement of ground water.

ACKNOWLEDGEMENTS

The author acknowledges the contribution of D. F. Barnes, U. S. Geological Survey, who conducted the gravity field operation in Searles Lake basin; L. C. Pakiser, U. S. Geological Survey, who supervised all phases of the work; W. C. Smith, T. W. Dibblee, and G. I. Smith, U. S. Geological Survey, who provided geologic background and guidance to assist in the conduct of the work.

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DEPARTMENTS

PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,730,673. J. J. Jakosky. Iss. 1/10/56. App. 1/20/47. Assign. Union Oil Co. of Calif.

Magnetometer. A d-c electromagnetic prospecting system in which current is passed between two spaced electrodes and the field observed at a point midway between them by means of horizontal and vertical pick-up coils connected to a magnetically-compensated galvanometer.

U. S. No. 2,731,596. J. R. Wait and A. A. Brant. Iss. 1/17/56. App. 2/21/52. Assign. Newmont Mining Corp.

Method and Apparatus for Geophysical Exploration. An electromagnetic prospecting system in which the exciting coil and the pickup coil are each in series with a common calibrated impedance network, the pick-up coil also having a null indicator in its circuit.

U. S. No. 2,731,598. E. Herbert. Iss. 1/17/56. App. 8/17/51. Assign. ½ to Elliot Marshall, ¼ to Ivan Thomas and ¼ to Whitney W. Potter.

Apparatus for Tracing Underground Cables and Detecting Flaws Therein. Apparatus for locating a buried conductor in which electric oscillators of different frequencies are connected to two ends of the cable and employing two pick-up coils tuned to the two frequencies and selectively connected to an indicator.

U. S. No. 2,735,980. J. R. Wait. Iss. 2/21/56. App. 12/23/53. Assign. Newmont Mining Corp.

Method of Geophysical Exploration. A transient method of electromagnetic prospecting in which a square-wave current is applied to the ground between two spaced electrodes for at least 100 milliseconds and the field-induced emf picked up by an exploring coil is observed on a c-r tube screen after a period of 50 microseconds subsequent to application of the current pulse.

GEOCHEMICAL PROSPECTING

U. S. No. 2,733,135. W. B. Huckabay. Iss. 1/31/56. App. 4/2/49. Assign. Socony Mobil Oil Co., Inc.

Method of Analyzing Earth Materials for Hydrocarbons. A method of analyzing soil samples for paraffin hydrocarbons by extracting the samples with a solvent and passing the extract through a column of surface-active material to separate constituents.

GRAVIMETRIC PROSPECTING

U. S. No. 2,732,717. F. N. Rothacker. Iss. 1/31/56. App. 10/29/49.

Gravity Meter. A conical pendulum type of gravity meter in which the pendulum is rotated at constant speed and deviations from a normal path are detected by pick-up coils connected to a c-r tube, or a simple pendulum whose plane of oscillation is slowly rotated and changes in amplitude observed.

U. S. No. 2,732,718. B. Cornelison. Iss. 1/31/56. App. 8/24/51. Assign. Texas Instruments Inc.

Gravity Meter. A Worden type gravimeter which is fully temperature compensated over a wide

† Gulf Oil Corporation, Patent Department.

range of total gravity by means of an arm and frame of different materials in the nulling system so that the degree of compensation is adjusted simultaneously with changes in gravity.

U. S. No. 2,738,676. S. P. Worden and B. Cornelison. Iss. 3/20/56. App. 1/23/50. Assign. Texas Instruments Inc.

Large Range Gravity Sensitive Instrument. A Worden type gravimeter in which the nulling system has independently-adjustable strong and weak springs for coarse and fine adjustment or in which controlled electrostatic or electromagnetic forces are used in place of the weak spring.

MAGNETIC PROSPECTING

U. S. No. 2,730,063. R. W. Gebs and B. W. Ridley. Iss. 1/10/56. App. 11/10/52.

Degaussing System. A degaussing system in which the currents in quadrature coils are controlled from a compass-actuated synchro transmitter and a synchro differential generator which is adjusted for deviation.

U. S. No. 2,735,063. E. O. Schonstedt and H. R. Irons. Iss. 2/14/56. App. 8/6/52. Assign. U.S.A.

Total Field Magnetometer. A self-oriented total-field airborne magnetometer in which the detector head is pendulously suspended by a second gimbal to provide a vertical reference for the orienting elements, orientation of the measuring element with respect to the vertical and with respect to the aircraft heading being recorded by means of self-synchronizing servos.

U. S. No. 2,736,822. W. C. Dunlap, Jr. Iss. 2/28/56. App. 5/9/52. Assign. General Electric Co.

Hall Effect Apparatus. A Hall-effect device having a germanium plate with a particular type of polarity conductivity and with two pairs of electrodes on opposite edges of the plate, one of the input electrodes being of a charge-emitting type whose charge is opposite to that of the conductivity type of the germanium plate.

RADIOACTIVITY PROSPECTING

U. S. No. 2,733,355. T. M. McKee. Iss. 1/31/56. App. 2/19/52. Assign. Texaco Development Corp.

Thermal Neutron Measuring. A scintillometer for thermal neutrons having indium foil immersed in a transparent liquid luminophor.

U. S. No. 2,735,946. W. M. Stratford, C. F. Teichmann and G. Herzog. Iss. 2/21/56. App. 8/3/51. Assign. The Texas Co.

Prospecting. A radioactivity prospecting method in which the intensities of alpha, beta, and gamma radiation are measured along a traverse and the ratio of their intensities compared with corresponding ratios across a known anomaly.

U. S. No. 2,735,953. A. L. Tirico. Iss. 2/21/56. App. 3/38/52. Assign. The Texas Co.

Radiation Detector. A multiple-cathode Geiger-Mueller detector in which the cathode plates are made of resistive material and a current passed through them so that auxiliary fields between the plates will force charged particles toward the region of a higher potential anode.

U. S. No. 2,738,431. G. Herzog. Iss. 3/13/56. App. 2/14/52. Assign. The Texas Co.

Multiple-Plate Radiation Detectors. A multiple-cathode Geiger-Mueller detector having an array of parallel spaced cathode plates made of resistive material and an anode wire passing through concentric holes in the plates, a radial current being passed through the plates from the hole to the periphery so as to set up a potential field which draws ionized particles to the anode from the space between cathode plates.

U. S. No. 2,739,242. F. C. Armistead. Iss. 3/20/56. App. 5/31/52. Assign. Texaco Development Corp.

Radiation Detectors. A radioactivity detector having a principal scintillometer and an associated cosmic-ray detector which independently detects cosmic-rays by the Cerenkov effect light emission, a coincidence circuit being arranged to suppress output pulses originating from cosmic rays.

U. S. No. 2,739,286. R. W. Schede. Iss. 3/20/56. App. 9/1/50. Assign. U.S.A.

Alpha Survey Meter Circuit. An ionization chamber amplifier using an electrometer tube in an inverse feedback d-c amplifier circuit having a voltage compensating resistor to decrease grid-to-filament bias in response to a decrease in filament current.

SEISMIC PROSPECTING

U. S. No. 2,729,094. R. G. Piety. Iss. 1/3/56. App. 9/15/50. Assign. Phillips Petroleum Co.

Apparatus for Testing Seismometers. A device for testing a well geophone having a series of balls in a container above the geophone, a ball being dropped by a thermally-actuated release when current is applied to the device so that the resulting kick may be observed.

U. S. No. 2,729,300. L. R. C. Paslay, G. M. Pavey, Jr. and F. P. Wipff. Iss. 1/3/56. App. 11/29/49. Assign. Marine Instrument Co.

Water Borne Means for Making Seismic Surveys. An oil-filled detector streamer having spaced detectors and arranged to have slight positive buoyancy except at spaced weights and with a depressor at the front end of the streamer and a weight at the far end so that when cable is slacked off from the boat the front end and weights sink to bottom but the intervening parts of the streamer rise slightly off bottom.

U. S. No. 2,730,187. J. E. Hawkins and W. E. Pugh. Iss. 1/10/56. App. 1/11/47, 6/13/52 and 3/3/53. Assign. Seismograph Service Corp.

System and Method of Generating Seismic Waves in the Earth. A seismic shooting method using a center shot hole surrounded by a group of deeper shot holes with the center charge detonated later than the surrounding charges so that the resultant effect is a downwardly-directed wave.

U. S. No. 2,732,025. B. D. Lee. Iss. 1/24/56. App. 2/1/50 and 2/26/54. Assign. The Texas Co.

Method and Apparatus for Analysis of Seismographic Records. A system for photoelectrically compositing the tracks of a variable-area seismograph record in which the record is scanned by a series of slits which are displaced with respect to each other by cords connected to pantographs which adjust the slits for step-out time.

U. S. No. 2,732,536. H. B. Miller. Iss. 1/24/56. App. 5/5/50. Assign. Clevite Corp.

Cylindrical Electromechanical Transducer. A hydrophone made of a hollow cylinder of electromechanically-sensitive material with the outer surface exposed to acoustic pressure and the inner surface acoustically shielded, the length of the cylinder being less than half its circumference.

U. S. No. 2,732,906. W. H. Mayne. Iss. 1/31/56. App. 7/7/50. Assign. Olive S. Petty.

Seismic Surveying. A method of seismic shooting in which both the detectors and shot point are moved so that successive shots will have the same reflection points and adding the traces from the two shots.

U. S. No. 2,733,412. W. A. Alexander and J. T. Baker. Iss. 1/31/56. App. 11/19/51. Assign. Esso Research and Engineering Co.

Seismic Amplifier Interference Eliminator. A system for eliminating highline pickup by connecting a potentiometer across the geophone line with its adjustable contact grounded and also generating

an adjustable 90° phase-shifted voltage from a pair of equal resistors across the geophone line and applying the latter as a bucking voltage to each geophone line through a transformer with two secondaries.

U. S. No. 2,733,597. H. C. Hardy. Iss. 2/7/56. App. 7/12/52. Assign. Armour Research Foundation of the Illinois Institute of Technology.

Apparatus for Measuring Vibrations. A vibration measuring device having a sound transmitter of fixed frequency whose energy is reflected from the vibrating surface and picked up by a receiver connected to a descriminator which detects frequency shifts due to the Doppler effect at the vibrating surface.

U. S. No. 2,735,303. R. J. Haase. Iss. 2/21/56. App. 8/3/53. Assign. Shell Development Co.

Seismic Depth Gauging System. A gage for determining the depth of submersion of an oil-filled marine seismic streamer having an electromagnet which attracts an armature against the hydrostatic pressure, the electromagnet being connected in series with a rheostat and meter and a thyratron alarm which trips when the armature snaps against the magnet.

U. S. No. 2,735,503. R. B. Rice and S. D. Elliott. Iss. 2/21/56. App. 11/28/52. Assign. Phillips Petroleum Co.

Method of Seismic Prospecting. A method of preparing a shot hole in unconsolidated material by gradually springing the hole with small charges under water tamping to produce a spherical cavity with compacted walls in which an efficient seismic charge is fired.

U. S. No. 2,735,949. B. Podolsky. Iss. 2/21/56. App. 6/11/54.

Electrolytic Acceleration Sensing Device. An electrolytic accelerometer having an insulating capillary tube with globules of mercury separated by dilute electrolyte and having mercury-wettable rings on the inner surface of the tube to keep the mercury globules in place, terminals being provided at the ends of the tube contacting the end globules of mercury.

U. S. No. 2,738,488. J. D. MacKnight. Iss. 3/13/56. App. 1/18/50. Assign. The Texas Co.

Marine Cable for Seismic Surveying of Submerged Areas. A geophone cable for use in water-covered areas which has a rectangular metal strip wound on its outer surface in an open spiral so that the cable will cut into the bottom and bury itself when dragged over the water bottom.

U. S. No. 2,739,297. J. V. Atanasoff and E. R. Kolsrud. Iss. 3/20/56. App. 4/29/52.

Low Frequency Vibration Detection Device. A variable-capacity type seismometer having a movable condenser plate suspended between two fixed plates so as to modulate a carrier frequency and with d-c potentials applied to the plates to provide electrostatic forces which control centering and frequency, and the output signal differentiated and applied to the plates to set up electrostatic damping forces.

WELL LOGGING

U. S. No. 2,729,100. M. G. McCool and C. O. Moorhead. Iss. 1/3/56. App. 8/10/53.

Well Drilling Recorder. A drilling rate recorder having a recording line with beads attached at fixed distances and a recorder arm which is moved by the bead to mark a moving tape and which rocks to release the bead at the limit of its travel so as to pick up the next bead.

U. S. No. 2,729,101. B. F. Wiley. Iss. 1/3/56. App. 7/9/51. Assign. Phillips Petroleum Co.

Flowmeter. A well flowmeter having two parallel flow channels with a motor-driven impeller in one channel and a thermal-type flow detector in the other channel, the motor speed being adjusted from the surface to effect zero flow in the second flow channel and the motor speed indicated.

U. S. No. 2,729,783. R. G. Piety. Iss. 1/3/56. App. 2/6/50. Assign. Phillips Petroleum Co.

Method and Apparatus for Electrical Well-Logging. An electric logging system in which one electrode is in the form of a cage with bowed springs which engage the borehole wall and having considerable play on the main cable so that a different electrode spacing prevails when moving the electrodes up the hole than when moving downward.

U. S. No. 2,729,784. R. E. Fearon. Iss. 1/3/56. App. 11/30/50. Assign. Lane-Wells Co.

Method and Apparatus for Electric Well Logging. A method of electric logging through casing by establishing longitudinal current flow in two casing sections in opposite directions and controlling the flow in response to the potential developed between intermediate points of the casing, and measuring the potential from a mid-point between the current flows to the intermediate points.

U. S. No. 2,730,672. W. D. Mounce. Iss. 1/10/56. App. 10/18/48. Assign. Esso Research and Engineering Co.

Electrical Resistivity Well Logging Systems and Methods. An electric logging system in which the potential electrodes are on a short cable extended below the current electrode by a small motor-driven reel, so that a section of log may be taken with the current electrode fixed and only the potential electrodes moving, after which the current electrode is moved to a new location and the potential electrodes moved over a new section of hole.

U. S. No. 2,731,826. B. F. Wiley. Iss. 1/24/56. App. 10/30/51. Assign. Phillips Petroleum Co.

Apparatus for Detecting Leaks in Gas Wells. A gas flow detecting device having a small orifice and thermocouples or resistances in the gas stream on the two sides of the orifice whose temperature difference is indicated.

U. S. No. 2,732,518. J. M. Bricaud. Iss. 1/24/56. App. 11/22/52. Assign. Borg-Warner Corp.

Bore Hole Detecting Circuit and Bore Hole Firing Circuit Utilizing a Common Transmission Channel. A combined casing-collar locator and perforating gun operating on a single conductor cable having a high impedance magnetic pick-up coil in parallel with a rectifier and the shot, and a switch at the surface to connect the device either to a galvanometer or to the firing circuit.

U. S. No. 2,732,525. A. Blanchard and M. Mennecier. Iss. 1/24/56. App. 6/27/52. Assign. Schlumberger Well Surveying Corp.

Electrode Carrier Means for Well Logging Apparatus. An electrode carrier having bowed springs with a liquid-filled cushion between the spring and the borehole wall and electrodes on the outer face of the cushion.

U. S. No. 2,732,714. A. D. Bennett. Iss. 1/31/56. App. 7/23/52. Assign. Stanolind Oil and Gas Co.

Measurement of Annulus Volume in Wells. A method of logging open-hole annulus volume in a pumping well by allowing the well to reach a condition of static fluid level, then pumping from the bottom and simultaneously introducing liquid at the same rate on a weight basis, and observing the movement of the fluid interface by means of electrodes on a cable.

U. S. No. 2,733,353. S. J. Pirson. Iss. 1/31/56. App. 7/3/51. Assign. Stanolind Oil and Gas Co.

Auto-Radiography of Wells. A method of determining the character of formation pores by depositing a radioactive material in the formation openings exposed to the borehole and subsequently holding a photographic film in contact with the borehole wall to obtain a radiograph of the openings.

U. S. No. 2,733,519. I. Murata. Iss. 2/7/56. App. 10/27/51 and 10/9/52.

Deep Well Surveying Instrument. A well surveying apparatus having a magnetized chart carrier which is initially clamped and released when the instrument is at the desired depth to permit orienta-

tion of the carrier by the earth's magnetic field whereupon the carrier is again clamped and moved upward against a pointed pendulum.

U. S. No. 2,733,599. L. W. Storm. Iss. 2/7/56. App. 4/13/53. Assign. Warren Automatic Tool Co.

Traveling Block Position and Velocity Recorder. A drilling-rate recorder having a line connected to the traveling block and single-layer wound on a spring-retracted drum and recording rotation of the drum.

U. S. No. 2,733,605. J. R. Buck. Iss. 2/7/56. App. 1/26/51. Assign. Socony Mobil Oil Co., Inc.

Frequency Sensitive System for Measuring the Rate of Fluid Flow in a Well Bore. A well flowmeter having alternately energized heaters upstream and downstream of a temperature-sensitive element which changes the inductance in an oscillating circuit to change its frequency which is observed at the surface.

U. S. No. 2,736,197. R. L. Doan. Iss. 2/28/56. App. 1/2/51. Assign. Phillips Petroleum Co.

Apparatus for Determining Relative Permeability of Formations. A well flowmeter having a long perforated shell whose walls have pairs of insulated contacts and a sliding contractor which is moved longitudinally inside the shell by fluid flow and which successively interconnects contacts to close an indicating circuit at the surface.

U. S. No. 2,736,967. H.-G. Doll. Iss. 3/6/56. App. 2/9/52. Assign. Schlumberger Well Surveying Corp.

Induction Caliper. A caliper logging device having a coil on a caliper arm and a coil on the body of the instrument, changes in the inductive coupling of the coils being detected.

U. S. No. 2,737,595. S. A. Scherbatskoy. Iss. 3/6/56. App. 11/8/52.

Cross Feed Indicator for Simultaneous Radioactivity Well Logging System. A circuit for detecting cross fed in a multichannel well-logging system arranged to give an indication whenever signal of one channel is transmitted through another channel.

U. S. No. 2,737,639. G. C. Summers and J. O. Ely. Iss. 3/6/56. App. 3/23/53. Assign. Socony Mobil Oil Co., Inc.

Electromechanical Acoustic Pulser. A periodic pulse source for an acoustic logging device having a magnetostrictive transducer connected to a gas-discharge tube and condenser which is charged by rectified a-c supplied at low voltage from the surface of the ground.

U. S. No. 2,737,864. R. P. Gutterman and C. G. Small. Iss. 3/13/56. App. 11/9/51. Assign. U.S.A.

Borehole Camera. A camera which photographs the borehole wall by means of a mirror and in which the film advance and flash illumination are automatically controlled by contacting cams on the sheave traversed by the supporting cable.

U. S. No. 2,739,475. T. J. Nowak. Iss. 3/27/56. App. 9/23/52. Assign. Union Oil Co. of Calif.

Determination of Borehole Injection Profiles. A method of determining the injection profile of a well by running a temperature log under steady state injection of fluid, then shutting-in the well until flow ceases and running a second temperature log with the well shut in and comparing the two logs.

U. S. No. 2,739,476. E. R. Atkins, Jr. Iss. 3/27/56. App. 5/15/50. Assign. Union Oil Co. of Calif.

Electric Flowmeter. A flow meter for an injection well having two spaced probes in a flow tube with the probes connected to an oscillator so that change in the ambient fluid at the probe changes the output of the oscillator which is observed at the surface, and adding to the injection fluid a detectable tracer whose arrival time at the probes is observed.

U. S. No. 2,740,051. S. A. Scherbatskoy. Iss. 3/27/56. App. 10/21/50. Assign. Perforating Guns Atlas Corp.

Radioactivity Well Logging Apparatus. A combined radioactivity and casing-collar logging apparatus in which the radioactivity detector produces uniform pulses whose rate indicates the detected radioactivity and the collar detector produces a voltage kick whenever the apparatus traverses a collar and using a single-conductor cable with filters to separate the signals of the surface.

U. S. No. 2,740,052. J. H. Castel and S. A. Scherbatskoy. Iss. 3/27/56. App. 10/21/50. Assign. Perforating Guns Atlas Corp.

Radioactivity Well Logging Apparatus. A combined radioactivity logging and casing-collar finding apparatus in which the radioactivity detector produces pulses whose rate indicates the detected radioactivity and the collar finder produces unidirectional signals whose magnitude indicates proximity to a casing collar, a-c power to the well apparatus and the indicating signals to the surface being transmitted over a single-conductor cable.

U. S. No. 2,740,053. S. A. Scherbatskoy. Iss. 3/27/56. App. 1/12/51. Assign. Perforating Guns Atlas Corp.

Radiation Well Logging System. A system for simultaneously making a neutron and gamma-ray log and a correlated casing-collar log over a single-conductor cable in which the neutron and gamma-ray measurements are transmitted to the surface by means of oppositely-directed pulses and the collar-locating coil is in an a-c bridge circuit whose balance condition is transmitted to the surface as a d-c voltage.

MISCELLANEOUS

U. S. No. 2,730,714. E. H. Mahoney. Iss. 1/10/56. App. 4/23/54. Assign. Seismograph Service Corp.

Radio Location System. A position determining system using three spaced transmitters each radiating two carrier waves and a spaced reference receiver which heterodynes the signals in pairs and modulates the signal of the center transmitter.

U. S. No. 2,733,005. J. E. Sherborne and E. R. Atkins, Jr. Iss. 1/31/56. App. 3/16/51. Assign. Union Oil Co. of Calif.

Potentiometric Oil Reservoir Model. A potentiometric model in which an insulating sheet has deposited on it conducting layers which are analogous to formations and of conductivity proportional to permeability and also has a conducting sheet with layers whose resistivities are proportional to porosity and correspondingly-located contactors on the two assemblies are interconnected so that the current in the porosity model is determined by the voltage gradient of the permeability model.

U. S. No. 2,734,682. F. M. Mayes. Iss. 2/14/56. App. 7/18/50 and 8/19/54. Assign. Sun Oil Co.

Method for Least Squares Adjustment of Survey Nets. An electric analog network for adjusting survey nets in which junctions correspond to meshes of the net and conductances between junctions are proportional to lengths of the net lines, and currents from external sources are introduced at the junctions in proportion to the survey closure of the corresponding net.

U. S. No. 2,735,652. E. F. Brady. Iss. 2/21/56. App. 3/20/50. Assign. Eastman Oil Well Survey Co.

Core Taking and Orienting Method. A system for marking the orientation of a core in which the core is cut and before breaking it off a wire-line drift indicator is run which is oriented by magnets on the drill pipe and marks a landing plate on the core barrel, after which the drill pipe and core barrel are removed and the orientation of the core with respect to the magnets marked on the core.

U. S. No. 2,735,999. W. M. Ross. Iss. 2/21/56. App. 8/3/48, 2/16/52 and 6/10/52. Assign. Minneapolis-Honeywell Regulator Co.

Echo System for Determining Nature of Sea Bottom. An echo-sounding system in which a supersonic pulse is transmitted and the received reflected signal is mixed with a steady oscillator signal to produce an audible beat signal having a discernible character dependent on the character of the reflecting surface.

U. S. No. 2,736,099. R. G. Fischer. Iss. 2/28/56. App. 8/18/52. Assign. Socony Mobil Oil Co., Inc.

Core Sample Micrometer. A device for quickly measuring dimensions of a core sample having a vertical rod whose tip is moved downward against the sample resting on a base plate, the rod being moved by a gear and rack which also drives a dial from which the dimension is read.

U. S. No. 2,737,646. G. Muffly. Iss. 3/6/56. App. 6/12/52. Assign. Gulf Research & Development Co.

Transient Viewer and Recorder. Apparatus for viewing a slow transient on a c-r oscilloscope by recording the transient on a rotating magnetic record medium and playing the record back at a higher repetitive rate so that a large part of the transient may be continuously observed.

U. S. No. 2,737,804. G. Herzog and K. C. Ten Brink. Iss. 3/13/56. App. 6/13/51. Assign. The Texas Co.

Relative Permeability Measurements. A method of determining relative permeability of core samples in which the effect of the accompanying immobile phase is produced by injecting the desired amount of a molten material which solidifies in the sample, petroleum wax being injected into a dry core to simulate a wetting phase or low-melting-point alloy being injected to simulate a non-wetting phase.

U. S. No. 2,739,249. V. O'Gorman and R. R. Perron. Iss. 3/20/56. App. 9/20/54. Assign. United Shoe Machinery Corp.

Velocity Pickup Devices. A velocity pickup for a moving ferromagnetic machine part in which an elongated magnetic field is set up transverse to the motion and elongated in the direction of motion and a conducting sheet connected in a low impedance circuit placed between the moving part and one of the pole pieces.

U. S. No. 2,739,296. S. W. Woodward. Iss. 3/20/56. App. 11/27/48. Assign. Marine Marker Corp.

Marine Marker. An under-water location marker having a spring motor which controls operation of an electric motor-driven striker and an electric motor-driven rewind mechanism connected to the spring motor by a second spring.

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REVIEWS

REVIEWS COMMITTEE

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Arctic Research, Diana Rowley, editor, The Arctic Institute of North America, Montreal, Canada' 1955, +261 pp. 1 map.

"The Arctic Institute of North America is concerned with the prosecution of research in the arctic and subarctic regions of the North American continent and in Greenland." This is a direct quotation from the introduction to this volume by Dr. R. C. Wallace, Executive Director of the Institute from November, 1951, to January, 1955, the time of his death. Dr. Wallace was primarily responsible for the publication of this volume which is the joint effort of many writers associated with the various programs of research in the areas indicated and which have been underway for several years. The book describes the problems and results obtained in three principal fields, (1) Physical Sciences, (2) Biological Sciences, and (3) Social Sciences. Each Section consists of a number of short articles on special topics. The geophysicist is immediately concerned with that portion of the book on physical sciences. This section contains the following articles:

Meteorological activities in the Canadian Arctic. R. W. Rae
Research in geology and geomorphology in the North American Arctic and Subarctic. John C. Reed and Hugh S. Bostock
Glaciology. P. D. Baird and R. P. Sharp
Permafrost research. R. F. Legget
Geophysical Research in Alaska. L. O. Colbert
Geophysical exploration in Alaska. H. R. Joesting
Problems of geophysics in the Canadian Arctic. C. S. Beals, J. H. Hodgson, M. J. S. Innes, and R. G. Madill
The ionosphere over northern Canada. Frank T. Davies
Geodetic investigations in the Canadian Arctic. J. E. R. Ross
Oceanographic problems of the Arctic Ocean. C. O'D. Iselin
Tidal data in the North American Arctic. L. O. Colbert
Sea ice studies. Terence Armstrong

These chapters outline the work which has been done in the fields of geomagnetism, geological and radioactivity surveys, seismology, and geothermal studies. Gravity determinations and seismic surveys have been used to determine at various places the thickness of the ice cap and in the study

of permafrost. Pendulum observations were made in the arctic as early as 1819–20, and many pendulum and gravimeter stations have since been established. Geological research has been underway for several years and many maps have been published. Meteorological activities in the region are described, as also are the programs of permafrost research, ionosphere research, sea ice studies and rather extensive geodetic investigations which involve methods of astronomical determinations, triangulation, and shoran programs.

The geophysicist will find the portion of the book on biological and social sciences both informative and interesting to read. Certain phases of these subjects are of great importance to anyone who has any connection with the practice of geophysics in the subarctic regions of Canada, and for such persons the entire book is recommended reading. The book contains good bibliographies, and a complete list of research projects sponsored by the Arctic Institute.

J. E. Owen
Geophysical Research Corporation
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The Crust of the Earth (A Symposium), *Special Paper 62*, Arie Poldervaart, editor, The Geological Society of America, New York, N. Y., 1955+762 pp., $6.50.

To mark the Bicentennial of Columbia University in 1954, its Department of Geology sponsored a symposium on *The Crust of the Earth*. The resulting papers have been gathered together and published by the Geological Society of America as its *Special Paper 62*. Physically it is , of course, not a "paper," but a well bound book beautifully printed by the Waverly Press.

Because the Symposium was planned to be a survey of the many different facets of knowledge concerning the earth's crust, and because the authors of the papers are authorities in their fields, this volume is one which will be a very important reference work for many years.

The Crust of the Earth is not much concerned with the superficial skin of sedimentary layers which forms the happy hunting ground of the economic geophysicist. The term is used to designate the outer layers of the earth above the Mohorovicic discontinuity of seismic fame, hence including roughly the materials to a depth of 35 to 40 kilometers, although some contributors prefer to define the crust of the earth as a somewhat thicker layer, some 100 kilometers in thickness.

Geologists and geophysicists who are interested only in the purely practical problems of prospecting will find but few pertinent papers in this volume, but all who aspire to be earth scientists in even a small way, should certainly add it to their library. It is a really great collection of very excellent papers.

It is impossible for any reviewer to do justice to a book such as this. Since it contains 44 papers by many more authors, even a brief comment on each can hardly be included in a short review. About all this reviewer can do is to indicate the vast scope of the work and mention particularly some of the material of most interest to him.

The book is organized into four parts covering the following very general topics:

Part I. *Nature of the Earth's Crust*
Part II. *Recent Deformation and Sedimentation*
Part III. *Structural Synthesis and Petrogenesis*
Part IV. *Historical Development of the Earth's Crust*

In the first section, two papers deal with the contrast between Continents and ocean basins. Maurice Ewing and Frank Press discuss the geophysical differences while James Gilluly discusses the geological features. Seismic refraction surveys made in recent years have been the most powerful means of studying the ocean basins. They have established without doubt that the Mohorovicic discontinuity lies only 10–11 Km. below the surface of the sea as against some 35–40 Km. beneath continental surface. The silicic crust beneath ocean basins is only about one-fifth as thick as that below continents. In general, seismic and gravity data agree that there is isostatic equilibrium between continents and ocean basins. Many problems still remain, these being primarily concerned with the conditions in the borderland between continents and ocean basins.

Beno Gutenburg summarizes available information concerning the velocities of elastic waves in the earth, obtained from earthquake data and some man-made explosions. Using these data he proposes several possible structures for the earth's crust. Howard E. Tatel and Merle A. Tuve describe their widespread seismic explorations of the United States using large explosions. They find the first major discontinuity to be the Mohorovici; that the depth to this major increase in velocity is not constant over the continent, and that it has no apparent relationship to the altitude of the surface. In many areas they were able to obtain reflections from the "Moho" at a fairly critical shot-receiver distance of some 100 Km. Their work has led them to believe that many so-called phases on seismograms result from the conversion of body waves to Raleigh waves, and vice versa, at the irregular surface of the earth. If careful analysis of many records is not made these phases may be interpreted to indicate a layering of the crust which does not exist. As a result of their work, they propose a somewhat simpler model of the crust than those proposed by Gutenberg, one in which the velocity increases only slightly with depth for two-thirds of the crust thickness, then increases quite rapidly to the 8 Km. velocity below the "Moho."

Francis Birch discusses the physics of the earth's crust, telling what little is known about the physical properties of rocks as determined by field and laboratory measurements. He points out that it is now becoming possible to reproduce the ambient temperature and the stress at fairly great depths in the modern high-pressure laboratory so that much more realistic data may soon be obtained.

Arie Poldervaart reviews chemical data pertaining to materials of the crust and outlines the possible chemical evolution of the crust from earliest geologic times. Other articles in Part I deal with the use of earthquake surface waves as a means of studying crustal structure. and with the seismic evidence for tectonic activity and the nature of faulting. A chapter by T. L. Worzel and G. Lynn Shurbet uses seismic data to construct a section for continents and for ocean basins and these, together with gravity data, to deduce the structure of the Gulf Coast Geosyncline, The Bahama Platform, and the Puerto Rico Trench.

Part II contains several papers of more direct interest to petroleum geologists. Among these is a paper by Paul Weaver on the Gulf of Mexico, one by H. N. Fisk and E. MacFarlan on the late Quaternary deltaic deposits of the Mississippi River, and a paper by N. D. Newell on the Bahamian platforms. Other papers deal with the pelagic sediments of the Atlantic and of the Pacific, recent deformations of the earth's crust, and the structure of the Tongo and Puerto Rico Trenches.

Part III of the volume is concerned primarily with the problems of crustal deformation on the grand scale, and with the problems of petrogenesis. A paper by F. A. Vening Meinesz gives a semi-quantitative analysis of the hypothesis that great geosynclines result from the plastic buckling of the earth's crust. He feels that the hypothesis which attributes large scale deformation of the earth's crust to a wrinkling process by which the crust adapts itself to a shrinking core is inadequate to explain existing conditions; favoring instead the alternative hypothesis which looks to subcrustal flow as the cause of crustal movement. He derives formulae for plastic buckling and shows that development of geosynclines requires 20 to 40 million years of relatively quiet evolution until the continuing compressive stress produces a catastrophic stage of great folding and overthrusting of less competent surface layers. The analysis explains quite well the belts of strong negative gravity anomalies, e.g., in the Indonesian Archipelago.

Sidney Paige of Columbia University discusses the same subject from a different point of view. He agrees with the hypothesis that the relatively light sialic continents have grown slowly throughout geologic time from small centers or lineaments to their present size. He is concerned with the source of energy required to produce this continuing flow and suggests that the fundamental force driving the evolution of the crust lies outside the planet, in the radiation of the sun. It is the radiant energy of the sun driving the hydrologic cycle which, coupled with the gravitational field of the earth, has built up through billions of years the light sialic continent segments. This process requires a continuing isostatic adjustment permitted by a plastic zone at reasonable depth.

Walter H. Bucher discusses deformation in orogenic belts. He describes the geological features of the great orogenic belts represented by the western Alps, and the southern Appalachians and their significance. He concludes his discussion by saying: "The deformation within the zones destined to become orogenic belts begins with the crust bending down over constrictions in an actively shrinking

subcrustal shell beneath which lie the zones of deep-focus earthquakes. Sedimentation in the deepening geosyncline may accentuate the process. Sooner or later the state of all-sided compression will cause the crust to fail by one side shearing across in low-angle thrusts. Simultaneously, superheated water and volatiles escaping from the subcrust produce regional metamorphism and plutonic rock bodies. Compression of the zone thus weakened drives out yielding blocks of geosynclinal zone as crustal folds which lengthening upward, become recumbent folds or thrust blocks. Piling up, generally but not necessarily, on one side and advancing under the combined action of the pressure behind them and gravity acting on them, these advancing recumbent folds or thrust masses cause the sedimentary cover to "peel off" far beyond the borders of the active zones, producing the phenomena of marginal deformation."

Three other papers in Part III deal with the role of water in petrogenesis; considering its importance in rock melts, in metamorphism and in hydrothermal alteration and weathering. A paper by Hans Romberg considers the kinetics of rock formation from the thermodynamic point of view. Another paper, by H. H. Hess, discusses the relationship of serpentine belts to orogeny and epeirogeny, while H. H. Read similarly considers granite series in mobile belts. Earl Ingerson discusses geologic thermometry, examining critically methods of measuring and estimating temperatures of geologic processes.

Two of the papers in Part III are somewhat different than the others, in that they deal primarily with geological observational data. One of these, by D. F. Hewett, describes the structural features of the Mojave Desert region as disclosed by very recent surveys. John Imbrie has a paper on biofacies analysis (the study of the total recognizable organic content of stratigraphic units), which should be of interest to paleontologists.

Part IV is concerned with the history of the earth's crust. It opens with four papers dealing with the geological time scale. R. C. Moore of the University of Kansas discusses the characterization of major and minor divisions of the geologic time scale in terms of their contained invertebrate fauna, while J. T. Gregory of Yale University outlines the very incomplete record of the vertebrates. Erling Dorf of Princeton University has a paper dealing with fossil plants and their relationship to the record of fossil invertebrates and vertebrates.

A paper by J. Lawrence Kulp of the Lamont Geological Observatory gives a critical review of all the methods which have been used for isotopic dating. The errors in older work have now been recognized and recent determinations have pretty well established that the age of the earth is not less than 4.5 billion years, and probably not much greater. Determinations of the age of the various geologic periods are less firmly established, and very little is yet known about the age of sedimentary strata. Research in this field is being actively pursued. Within the last few years the very promising potassium-argon method has been developed. Although there are difficulties to be overcome, it is potentially the most important method of determining geologic age, since potassium is a very common element in important rock types. The isotope K^{40}, which occurs in natural potassium to the extent of 0.0119 percent, decays to Ca^{40} and also to A^{40}. Study of this latter type decay is most promising for dating purposes since there is essentially no A^{40} in an igneous material at the time of its formation.

Other papers in this section deal with the development of the hydrosphere and atmosphere, deposition and subsidence, and the timing of orogeny and vulcanism.

Upon completing the perusal of the volume under review, the reader can not help wondering at the audacity of Man in even attempting to unravel the history of an earth which extends through billions of years in time, and his attempts to probe into its depths with tools hardly more adequate for his purpose than those used by prehistoric man seeking to change his environment. As long as human life goes on, this earth of ours will be a source of problems sufficient to challenge the imagination of the most brilliant theorists and the ingenuity of the most capable experimenters. Conflicting observational data and controversial hypotheses will always confront the earth scientist. One wonders what a volume similar to this one will contain when published by Columbia University during its Tri-Centennial in 2054! Certainly, the authors of that hypothetical volume will pay tribute to the labors of men whose work has here been so inadequately discussed.

W. T. Born

Economic Geology—Fiftieth Anniversary Volume, The Economic Geology Publishing Company, Urbana, Illinois, 1955, in two parts, 1130 pp. $8.00.

This volume commemorates the fiftieth anniversary of the founding of the publication *Economic Geology*, which was for many years the only publication in the English language concerned with the application of geological principles to mineral deposits of economic value. Until the advent of the *Bulletin* of the A.A.P.G., it was the chief medium of publication for papers dealing with the geology of petroleum and some of the most important fundamental papers in this field are to be found in its pages. In 1923 it published one of the very early papers dealing with geophysical prospecting, a paper by Stephen Rybar entitled *The Eötvös Torsion Balance and its Application to the Finding of Mineral Deposits*. In recent years, comparatively few papers concerned with petroleum geology have been published so that the journal is now primarily of interest to geologists engaged in the search for minerals other than petroleum. To all readers of GEOPHYSICS working in that field, this Anniversary Volume is highly recommended.

Each of the 25 different papers contained in the volume is a review article prepared by an invited author, an authority in his field. There is a growing awareness of the need of review articles in all technical fields. It is a difficult task for any professional man to keep abreast of current literature in his field, and few ever find time to read pertinent citations in the literature of the past. The availability of review articles ably summarizing the work of the past and the state of present knowledge in any given field is of extremely great value. The Editors of *Economic Geology* are to be congratulated upon adapting a most fitting method of celebrating the anniversary of their journal.

The wide scope of the material included can best be illustrated by the following Table of Contents.

PART I

Economic Geology, Alan M. Bateman
Metallogenetic Provinces and Epochs, F. S. Turneaure
Thermal Springs and Epithermal Ore Deposits, Donald E. White
The Classification of Ore Deposits, James A. Noble
Structure of Hydrothermal Ore Deposits, H. E. McKinstry
The Zonal Theory of Ore Deposits, Charles F. Park, Jr.
Temperatures in and Near Intrusions, T. S. Lovering
Synthetic Minerals, W. A. Weyl
Hydrothermal Alteration as a Guide to Ore, George M. Schwartz
Oxidation of Copper Sulfides and Secondary Sulfide Enrichment, Charles A. Anderson
Methods and Problems of Geologic Thermometry, Earl Ingerson
Sedimentary Deposits of Rare Metals, Konrad B. Krauskopf
Origin of Uranium Deposits, V. E. McKelvey, D. L. Everhart, and R. M. Garrels.

PART II

Engineering Geology—A Fifty Year Review, Robert F. Legget
Influence of Geological Factors on the Engineering Properties of Sediments, Karl Terzaghi
Recent Developments in Clay Mineralogy and Technology, Ralph E. Grim
Properties of Calcium and Magnesium Carbonates and Their Bearing on Some Uses of Carbonate Rocks, D. L. Graf and J. E. Lamar
The Quantitative Approach to Ground-Water Investigations, John G. Ferris and A. Nelson Sayre
Time of Petroleum Accumulation, A. I. Levorsen
Coal Petrology, C. E. Marshall
The Use of Gamma Ray Measurements in Prospecting, William L. Russell
Economic Applications of Paleoecology, Samuel P. Ellison
Geophysics Applied to Prospecting for Ores, Louis B. Slichter
Minor Elements in Some Sulfide Minerals. Michael Fleischer
The Study of Pegmatite Deposits, Richard H. Jahns

As previously indicated, only a few of the articles are of direct interest to petroleum geophysicists. These are the chapters by Levorsen and by Russell. Levorsen, as to be expected of an oil-finder, relates his discussion of time of petroleum accumulation to the problem of exploration. He states, "Exploration is aided by first finding the combination of time of trap development and time of optimum physical conditions that form oil and gas pools of a region, and then attempting to locate unexplored traps with a like history." He discusses the time of accumulation of petroleum with reference to the time of formation of traps, the time of formation of reservoir rocks, the time of wide spread orogeny, and with respect to the hydrostatic pressure gradient in the reservoir rock; and gives some criteria which are helpful in determining the time of accumulation.

Russell discusses radioactivity well logging as well as radioactivity surveys made for the purpose of locating ore deposits. He mentions the attempts being made to locate oil by mapping surface radioactivity surveys but cautions that his mention of the subject should not be interpreted to mean that these efforts have been successful. He points out that an apparent relationship between oil field and surface radioactivity can be expected to occur by chance in a few cases, so that a statistical analysis of a very large number of surveys must be made to evaluate the method. The number of surveys published to date is much too small to permit of such study and hence no definite conclusions can be drawn.

The first part of the paper by Slichter on *Geophysics Applied to Prospecting for Ores* emphasizes, the economic aspects of finding ore bodies. He points out that, because of past efforts of prospectors, there soon will be small chance of finding any ore bodies visible in outcrops. Even though geophysical methods of exploring for ore bodies can probe only a few hundred feet of overburden, there must be a very large number of concealed bodies which they can find. The problem is to find them at a reasonable cost. Dr. Slichter advocates a three-fold approach to this economic problem. First, is a revision of mining laws to conform to changing prospecting conditions, and second, an application of quantitative analysis and mathematical statistical techniques to the planning of exploration programs. Finally, perhaps with tongue in cheek, he mentions the possibility of diverting into mining ventures the venture capital now being absorbed by pari mutuel betting and slot machines. He adds that "Canada seems to have shown how this rich source of funds may be put to useful work in prospecting."

As an example of the application of probability theory in mining prospecting he considers the planning of a core drilling program, the object being the maximization of the value of ore discovered in relationship to the total cost of prospecting. His treatment of this relatively simple problem requires 30 pages! Most prospecting problems are far more complicated. While admitting that the type, of analysis he proposes is difficult, and sometimes impossible, Dr. Slichter does argue strongly for a point of view which will encourage the substitution of quantitative analysis of problems whose solution is now sought only by educated guess.

The second part of Dr. Slichter's paper deals with the application of magnetic, electro-magnetic, gravitational, self potential, and resistivity methods in prospecting. The seismic method is mentioned only briefly because it has not yet been found to be of much value. In his discussion of these methods, the author gives numerous examples of the application of each method. The relatively new technique of airborne electromagnetic surveys is discussed with special reference to the successful work already done by the International Nickel Company. This portion of the paper should be of interest and considerable value to all geophysicists in the mining industry.

The review of engineering geology by R. F. Leggett should be of interest to geophysicists interested in the application of geophysical methods to civil engineering problems, although the author hardly mentions the use of geophysical methods in studying dam sites, searching for gravel deposits, and in road building. One gets the impression from this review article that the application of geological knowledge and of geophysical techniques to civil engineering work has been a slow and difficult process.

The few chapters specifically discussed in this review are only those of direct interest to geophysicists. Obviously they form only a minor portion of the text. The chief value of the book lies in the summaries of existing knowledge concerning the facts and theories pertaining to occurrence and genesis of ores of all types. This body of knowledge is basic to the development of all exploration techniques.

W. T. Born

Geologic Cross Sections, 1931–1955, John C. Maher, Bulletin Am. Assoc. Petroleum Geologists, Vol. 39, No. 7, pp. 1405–1416, July, 1955, Tulsa, Oklahoma, $2.00 single copy.

A committee of the American Association of Petroleum Geologists under the chairmanship of Grover E. Murray, and later, John C. Maher, has compiled a list of 115 geological cross sections prepared by some 23 geological societies, most of them local societies affiliated with the A.A.P.G. The compilation here published gives the geographical location of the cross section, the geological section included, the type of logs used (electrical, lithological, or both), and the datum plane of the section. Also shown is the year of compilation of each cross section, its size and price, together with the, address of the Society from which it may be purchased.

In the present compilation the sections are indexed only by a code number indicating the source. However, it is quite easy to look up cross sections available in a given geographical area since they usually were compiled by a Society located in the geographical region covered. It is expected that an index map will be published later.

It is believed that this compilation will be of interest to geophysicists as well as to geologists. All too often valuable information concerning any given area is not employed because of the difficulty of locating it. The compilation of indices of available information is not an easy task but is certainly a worthwhile project for a technical society. The constant daily use being made of the *Index of Velocity Logs*, sponsored by the Society of Exploration Geophysicists, well illustrates this point.

W. T. Born

Instrumentation and Methods for Radioactivity Detection in the Mineral Industry, J. O. Milmoe and S. P. Kanizay, Colorado School of Mines Quarterly, Volume 51, No. 1, Department of Publications, Colorado School of Mines, Golden, Colorado, $1.00 postpaid.

In view of the widespread interest in prospecting for radioactive ores, this issue of the Colorado School of Mines Quarterly should have a tremendous sale. It undoubtedly contains more information on the subject per dollar of cost than any other available publication.

The material presented is divided into two sections, and an appendix. The first section is written by James O. Milmoe, instrumentation chemist at the Colorado School of Mines Research Foundation. It deals with the theory, development, and application of the various instruments used to detect radioactivity. The second section, written by Stephen P. Kanizay, instructor in Geology at the School of Mines, deals with the actual field use of the various instruments and discusses the practical problems involved in applying current exploration techniques. The appendix gives much information of value to prospectors. It includes a list of establishments where ore samples may be assayed, schedules of prices for uranium ore, and information concerning the availability of airborne radioactive survey maps.

The authors of the volume have tried to present the material in a form which would be useful to geologists, to students, and to prospectors. This was a difficult task and, on the whole, it has been well done. While each of the three groups of readers might wish for different treatment of subjects of primary interest to them, they nevertheless will find much of interest and value. Considering the low cost of the book, it may well be purchased by anyone having more than a casual interest in the subject.

W. T. Born

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MEMORIAL

LAWRENCE F. ATHY

Lawrence F. Athy died unexpectedly of a heart attack December 17, 1955, in Giddings, Texas. Two previous attacks had forced an early but active retirement on September 1, 1955. At the time of his retirement he had served Continental Oil Company faithfully for more than 30 years. He divided his time between his home, his family and friends, and his ranch near Giddings. On his ranch was a lake where he could pursue his main hobby—fishing.

Lawrence F. Athy was born June 1, 1898, on a farm near Bryon, Ohio. He learned the value of hard work while helping his father on the farm. He attended high school at Stryker, Ohio. From 1915 to 1919 he attended Denison University and received the Bachelor of Science degree. His major subject was physics, but he also became interested in geology.

After teaching a short time in the high school science department at Kings Mills, Ohio, he enrolled in the Graduate School of Geology at the University of Chicago, where he became an outstanding student in petrography. Just before entering the University of Chicago, he married his sweetheart of Ohio farm days, Helen Thiel.

While attending the graduate school, he was employed by the Illinois Geological Survey. During the school term he was employed by the university to teach as a Fellow.

Lawrence received his Ph.D. degree in 1925 and was employed in the field of Petroleum Geology in the Geological Research Department of the Marland Oil Company at Ponca City, Oklahoma. His early work in this capacity allowed him to make several contributions to the literature on the study and interpretation of compaction of sediments.

The Marland-Continental merger of 1930 and the depression years were distressing. Lawrence, now known as "Doc," became interested in geophysics. He was in charge of magnetometer and torsion balance parties as well as refraction seismograph. He was made Acting Superintendent of the Geophysical Division in 1930 and became Superintendent of the Division in 1931. He was made Chief Geophysicist of Continental Oil Company in August of 1932.

Realizing the potential value of the reflection seismograph as a tool for the oil finder, he moved aggressively to build a modern Geophysical Department. Under his leadership and management, the department grew from a modest beginning to a well-rounded organization of more than 300 employees.

In 1949 Continental Oil Company executive headquarters was moved to Houston, Texas. "Doc" transferred to Houston at this time, and the following year was promoted to Exploration Manager for the company. He continued in this position until retirement in September of 1955. "Doc's" stimulating personality, honesty, practical-mindedness, sense of fair play, and versatile technical ability gained the respect, admiration, and confidence of all of his associates. The three sections within the Exploration Department were integrated and cooperated in a united effort to find oil. His active interest in the AAPG, SEG, and GSA provided current thinking on many phases of exploration.

Dr. Athy is survived by his wife, Helen, and his son, Larry, engaged in the engineering profession, both of Houston, Texas.

L. E. WHITEHEAD

March 9, 1956

MEMORIAL

FRANCIS LUTHER BISHOP

Francis Luther Bishop, 53, Consulting Geophysicist and Independent Oil Operator, died after a heart attack on October 26, 1955, at his home, 1642 E. 36th Street, Tulsa, Oklahoma. He was laid to rest the afternoon of October 29 in his family burial plot in the Cleburne Cemetery, Cleburne, Texas. To his many friends and associates he was always called "Bish."

He was born in 1904 in Cleburne, Texas, where his father was president of the Cleburne State Bank. Bish spent all of his early life at Cleburne where he gained his primary education, graduating from high school there. He was in the insurance business with the firm Bishop and Lain from 1925 to 1929, at which time he left Cleburne and traveled for two years for Frank Pearson Insurance Company of Chicago. In May of 1931 he became associated with Geophysical Service Inc. of Dallas. During this early period with the Company he served as permit man and surveyor. Some of his early survey work was actually a careful job of surface geology and was of considerable interest at the time. Promotion followed and in a short time he became a party chief in charge of one of the con-

tract seismograph parties for Geophysical Service Inc. In 1939 he opened the Tulsa, Oklahoma, office of Geophysical Service Inc. as manager.

In the latter part of November, 1941, resigning from his position with Geophysical Service Inc., Bish entered into a new phase of his life. At this time he opened an office in Tulsa, Oklahoma as a consulting geophysicist. This office and occupation he maintained until his death. However, added to this activity was that of independent oil operator, which resulted in the discovery of many oil fields wherein he retained an interest.

Although always maintaining allegiance to the State of his birth, he nevertheless became a member of many of the local organizations, including the Tulsa Club, Tulsa Chamber of Commerce, and Men's Dinner Club. Other organizations to which he belonged where American Association of Petroleum Geologists and Society of Exploration Geophysicists.

In May 1925 he married Vera Davis and to them a daughter, Nancy Sue was born. She is now Mrs. Richard W. John, living in Oklahoma City, and has three children, Richard Bishop, Judith Irene, and Nancy Sue.

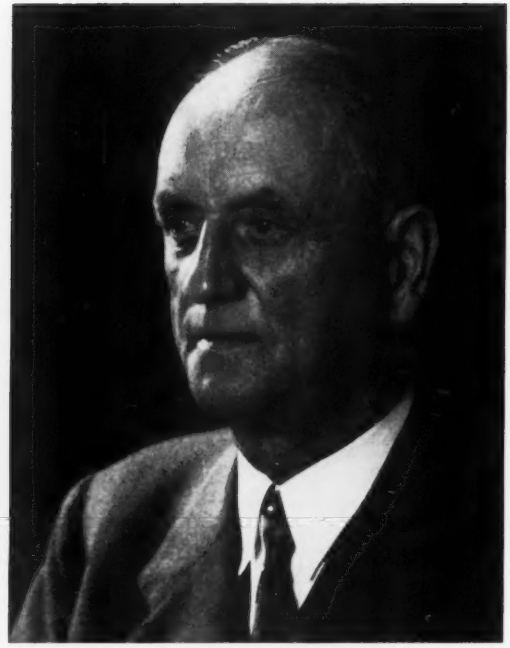
Bish was a person of great cheerfulness and life was always interesting to him; therefore, anyone associated with him found his own life brightened by the association.

F. L. Bishop will long be missed by his many friends and the Society has lost an outstanding member.

W. R. RANSONE

March 13, 1956

MEMORIAL



LUDGER MINTROP

On July 18, 1955, the friends and neighbors of Dr. Mintrop joined with him in celebrating his 75th birthday. They did so with enthusiasm and considerable fanfare. They were joined by representatives of various professional and civic organizations in which the celebrant had been, and continued to be, an active participant. Some of these representatives came from considerable distances to pay their tribute to a grand old man. The people of Werden, Germany, were honoring their most outstanding citizen.

On January 1, 1956, Ludger Mintrop died, mourned by his family, an unusually wide circle of friends and by a globe circling profession to which he had contributed much and by which he was greatly esteemed.

Dr. Mintrop's education was obtained at the Bergakademie in Berlin, at the Technische Hochschule in Aachen, and at the University of Goettingen. At the University he became a student of Wiechert under whose auspices Mintrop performed some experiments on the recording of artificial earthquakes and made some effort to deduce from them the structure of the terrain traversed. This work with Wiechert was apparently decisive in orienting his subsequent career.

After a spate of teaching at the Technische Hochschule at Aachen and the Bergschule at Bochum, Dr. Mintrop founded, in 1921 at Hannover, the Seismos Gesellschaft which is probably the first geophysical contracting organization to be established anywhere. Initially this organization utilized the seismic refraction

technique almost exclusively, but later included others also, for example, the gravity-pendulum as developed for Seismos by Berroth. The first work done by Seismos in the western hemisphere was the refraction work for the Mexican Eagle Oil Company in Mexico, begun in early 1923. Later that same year a refraction crew began operations in the United States for the Marland Oil Company and early the following year (1924) a second crew began work in the Gulf Coast area for Gulf Oil Corporation. The Orchard dome (Moore's Field) was the first discovery made. This was promptly followed by a considerable increase in the number of crews and in the number of oil field structures found.

In 1928 Dr. Mintrop was appointed to the newly established professorship of mine-surveying and geophysics at the Technische Hochschule at Breslau and in 1938, additionally, to membership in the Department of Natural Sciences at the University of Breslau. As a result of the Russian occupation, Dr. Mintrop left Breslau in 1945 and returned to his birthplace. After several semesters as substitute and guest professor at Aachen, he retired at the end of 1948 to his paternal farm.

In 1949 Mintrop attended the St. Louis meeting of the S.E.G. and presented a paper on the geological implications of seismic recordings made at the time of the huge planned explosion on Helgoland in 1947 and of other data from large earthquakes.

Since that time he has been active on various German and International geophysical agencies. These included the constituting session of the European Seismological Commission at Verona in 1950, the Congress of the International Union for Geodesy and Geophysics in Rome in 1953 and the International Committee for the seismic investigation of the deep underground of the Alps. He was present at the International Petroleum Congress in Rome in June, 1955, and a number of our members who were also there reported having stimulating visits with him.

All told Dr. Mintrop made 19 visits to the United States. Those of his friends who were fortunate to be visited by him will remember the cigar invariably clenched between his teeth, and remaining there throughout the conversation. This did not help the intelligibility any, but the good doctor always made up by friendly gesture whatever was lacking in the enunciation.

Dr. Mintrop was the recipient of an honorary degree from the Montanistishe Hochschule in Leoben (Austria) and an honorary member of no less than six of the numerous scientific, professional, and civic organizations of which he was a member and in which he took an active part.

In 1930 DeGolyer and Mintrop were elected as the first honorary members of our Society in recognition of their efforts in establishing geophysics in petroleum prospecting. It was an honor well deserved. Dr. Mintrop has left a stamp on seismic prospecting which will be recognized by many who never saw him. Those of us who were privileged to know him will remember him as an outstanding colleague and a wonderful person.

E. A. ECKHARDT

March 19, 1956

MEMORIAL

WILLIAM EMERSON PUGH

On January 3, 1956, William E. (Bill) Pugh passed away during his sleep from a heart attack. Although his death was not unexpected, for Bill had been in ill health for some time, it was a great shock to all his friends, since his strong heart and tenacity to life were a great part of Bill's character.

As far back as 1935 Bill suffered an attack of cancer which was surgically eradicated and resulted in a colostomy. Despite this terrific disability, and knowing that his life could be foreshortened at any time, he continued to be active both in his company duties, in athletics (such as bowling), and as an ardent fan of baseball. During the last several years, Bill was again subjected to surgery, and all who knew him marveled at his continuing enthusiasm, his will to live, and his good-humored outlook on life.

Born in Williamsport, Pennsylvania, on March 19, 1900, Bill attended grade school and high school in Williamsport and was graduated in 1916. For two years, 1919 to 1921, he was an underclassman at the United States Naval Academy, Annapolis. Upon leaving the Academy, he went to work for Dovola Products Company, Chicago. With his fine mind, Bill was attracted to geophysics and

entered the Colorado School of Mines in the late twenties and remained there until 1931, when he obtained a master's degree in Geophysics. His exploits in the School of Mines, and particularly his high scholastic attainments, are fondly remembered by his classmates.

Upon leaving the School of Mines, Bill joined Plains Exploration Company to conduct magnetic surveys. In December 1932 he came to work for Seismograph Service Corporation, and in early 1933 joined the writer in starting the first company-owned Cities Service Oil Company seismograph crew, which commenced operations out of Pratt, Kansas. He remained with Cities Service until 1934 and returned to Seismograph Service Corporation as a party chief. For this group he pioneered many of the reflection techniques which the company used in the Gulf Coast of Texas and later in Kansas and Oklahoma. In 1939 he returned to the Tulsa office as a party supervisor.

In 1945 he was made a senior research engineer and spent the remainder of his years with the company in this capacity. One of his outstanding accomplishments for the company was the compiling of a complete set of training manuals for all members of a seismograph party. This included texts, reading guides, and examinations. In 1954 he assisted in the teaching of geophysics at the University of Tulsa.

While studying under Dr. C. A. Heiland at the Colorado School of Mines, Bill was co-author with Dr. Heiland of an outstanding paper on magnetics, "Theory and Experiments Concerning a New Compensated Magnetometer System," which was published by The American Institute of Mining & Metallurgical Engineers. He will be remembered in the industry both by geologists and by geophysicists for his editing of two bibliographies published in 1950 and 1951 entitled "Bibliography of Organic Reefs, Bioherms, and Biostromes" and "Bibliography of Stratigraphic Traps." The care, exhaustive research, and enthusiasm with which he edited these publications, which have been distributed throughout the world, have earned him many favorable comments.

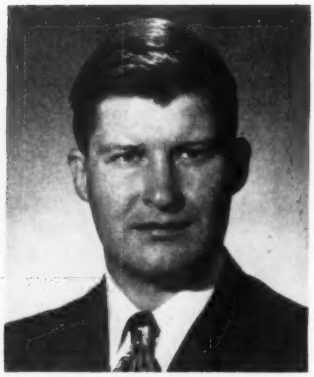
Married in the early 1930s to Miss Helen Gibson (deceased July 24, 1938), Bill was the father of one daughter, Mrs. Robert (Georgianna Pugh) March, who now lives in Chicago. In 1942 he married a second time, this time to Miss Pauline Wise, of Tulsa.

Bill was a member of Tau Beta Phi, Sigma Gamma Epsilon, and Kappa Sigma fraternities, and the Society of Exploration Geophysicists.

Bill will long be remembered by his friends as a man of the highest intellectual attainments, who through his most productive years had to suffer more or less constantly from his physical infirmity. Given good health, there would have been no limit to what Bill could have accomplished in his chosen field. We will miss greatly his grand sense of humor which was ever present, his easy friendship, and his penetrating knowledge in all fields of geophysics.

G. H. WESTBY

February 27, 1956



JAMES E. BERRY

JAMES E. BERRY was graduated from the University of Colorado in 1946, receiving a B.S. degree in electrical engineering. In 1947 he went to work for Seismograph Service Corporation. After working as a seismic observer for three years, including a two year term in Mexico, he entered the Colorado School of Mines. He enrolled in the Geophysics Department and received his M.S. degree in 1952. Since 1952 he has been employed at the Field Research Laboratories of Magnolia Petroleum Company in Dallas as a member of the well logging group. He is presently engaged in the interpretation of all types of well logs. He has been a member of the Society of Exploration Geophysicists since 1950.

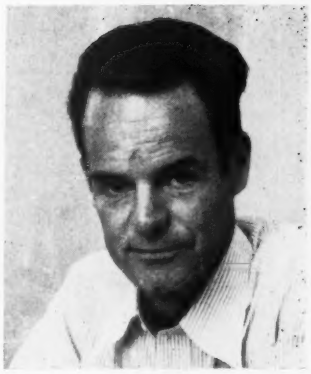
GEORGE J. BLUNDUN

GEORGE J. BLUNDUN, a Canadian by birth, received the degree of Bachelor of Science in mathematics and physics from the University of Saskatchewan in 1938. After having taught school for 9 years, he joined the Royal Canadian Air Force in 1940, and served as an air navigation instructor and staff officer for nearly 5 years. Upon discharge he joined a seismic party at Pincher Creek, Alta., as computer, interpreter, and then party chief for Gulf Research and Development Company. In September, 1948, he became chief geophysicist for Northwest Seismic Surveys Ltd. at Calgary, Alta. From March, 1953, to the present he has been the chief geophysicist for Oilwell Operators Ltd., Calgary, which company directs the exploration and development of Home Oil Company, Federated Petroleums, and United Oil Company.

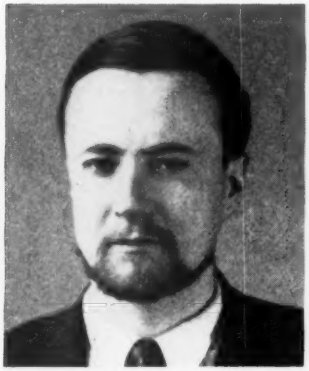
His general background is ten years of reflection seismic work in the Alberta and Saskatchewan plains, as well as Peace River, together with the refraction seismic work in the Alberta foothills.

He is a member of the Society of Exploration Geophysicists and the Canadian Society of Exploration Geophysicists.

RICHARD L. BURLING took his doctorate in experimental nuclear physics in 1941, working on atom-smashing electrostatic generators at the University of Wisconsin. He lost some interest in that field as it was increasingly applied to the destruction of human life and works. During most of his professional career, he has been teaching physics in colleges and universities, getting started in geophysics by being asked to teach a course at the University of Hawaii. The reflections of sound described in this issue of GEOPHYSICS, he noticed as a curious sideline while doing routine computations on seismograms with Western Geophysical Company's party 64 in Santa Barbara. Dr. Burling is also interested in the utilization of solar energy, particularly in underdeveloped parts of the world.



RICHARD L. BURLING



JÉRÔME CHASTENET DE GÉRY

JÉRÔME CHASTENET DE GÉRY is a native of Paris France. His mathematical studies in Paris were interrupted by World War II, during which he served as a volunteer for three years. After becoming "Licencié-ès-Sciences" in 1948, he entered the Aeronautique Research Institute (ONERA) where he was engaged in theoretical work on elasticity. During that time he taught modern mathematics to engineers. Since 1951 he has been with the Compagnie General de Geophysique, where he is chief of the mathematical section, dealing in particular with problems related to electric and magnetic interpretation.

M. Chastenet is a member of the "Société Mathématique de France" and the European Association of Exploration Geophysicists.

LACOSTE G. ELLIS

LACOSTE G. ELLIS received his B.A. degree from The Rice Institute in 1927. This was an academic degree with no major but covered general academic courses, including business administration and economics. He then specialized in physics and mathematics and obtained his M.A. degree in physics from Rice in 1929. He was an honor student during his four years of undergraduate work and a Fellow in Physics for the year 1928–1929. While attending Rice he also studied law one year at the South Texas School of Law (night school).

He joined Sun Oil Company in 1929 and since then has worked in the seismograph department successively as operator, party chief, technical head of seismograph department and at present is manager of seismograph exploration. He has been a member of The Society of Exploration Geophysicists since 1936.

STANLEY NEWTON HEAPS was born in Houston, Texas in 1917. He received his B.A. degree from Rice Institute in Houston, Texas in 1939 with physics as major. He received his B.S. degree from California Institute of Technology in 1940 with meteorology as major.

He was a meteorologist with Braniff Airways in Dallas, Texas in 1940. He was active in Dallas-Ft. Worth branch of American Meteorological Society. He obtained commercial radio telegraph and telephone licenses, and aircraft dispatchers certificate and ground school meteorology instructor rating. In 1945 he joined Magnolia Petroleum Field Research Department as computer for an experimental seismic crew; transferred to the Dallas Laboratory in 1949. He has been co-inventor on several geophone designs and seismic prospecting techniques.

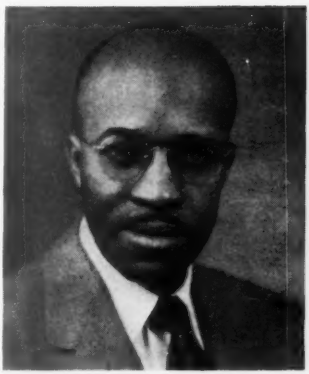
Mr. Heaps is a member of the Society of Exploration Geophysicists.

STANLEY NEWTON HEAPS

ROLAND G. HENDERSON received the bachelor's degree with majors in mathematics and physics from the Wisconsin State Teachers College, Milwaukee in 1935. He obtained his M.S. degree in mathematics from Atlanta University in 1939. From 1939 to 1941 he pursued graduate studies in mathematics and physics at the University of Wisconsin, and became a Julius Rosenwald Fellow there, 1940–1941.

He was employed by the Topographic Branch of the U. S. Geological Survey as a geodetic computer, 1942–1946, and as a geodetic engineer 1946–1947. During this time he did research in precision altimetry. In 1947 he transferred to the Aeromagnetic Section of the Geophysics Branch of the Survey where he has been engaged in geophysical research.

Mr. Henderson is a member of the National Honor Fraternity, Kappa Delta Pi; the American Geophysical Union; the Society of Exploration Geophysicists; and the Geological Society of Washington.



ROLAND G. HENDERSON

WARREN HICKS

WARREN HICKS graduated from the University of Texas in 1949 with a degree in electrical engineering and has been employed in the Field Research Laboratories of Magnolia Petroleum Company since that time. His first assignment was observer on a research seismic crew. He was later transferred to well logging research and has served as field logging engineer and now is specializing in interpretation of experimental logs. Mr. Hicks is a member of the Society of Exploration Geophysicists.

F. P. KOKESH

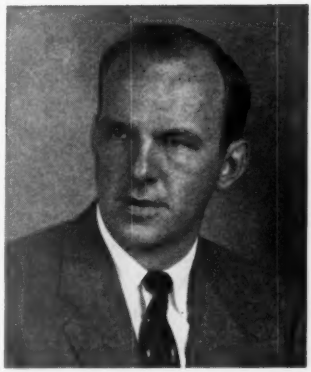
F. P. KOKESH was born in Hopkins, Minnesota. He received the degree of B.S. in electrical engineering in 1935 from the University of Minnesota, and in 1937 joined Schlumberger Well Surveying Corporation as field engineer. He became party chief and district engineer at Winnfield, La. in 1940. After serving with the United States Army Signal Corps and Air Corps from 1941 to 1945, attaining the rank of Lieutenant Colonel, Mr. Kokesh rejoined Schlumberger. He was district engineer at Monroe, La., and Harvey, La., division engineer of the Mississippi division at Jackson before joining the Schlumberger engineering staff at Houston in 1951. He is presently head of the geophysical engineering section.

Mr. Kokesh is a member of Eta Kappa Nu, American Institute of Mining and Metallurgical Engineers, Institute of Radio Engineers, and Society of Exploration Geophysicists.

GÉZA KUNETZ was born in Subotica, Hungary, a town which is now in Yugoslavia. He has lived in France since 1931, where he received the "Licencié-ès-Sciences" in 1934 and the doctorat of the Paris University (Sorbonne) in mathematics in 1937. In 1936 he had joined Society de Prospection Electrique (Schlumberger) where he was engaged in theoretical studies related to well logging. After World War II he was transferred to the sister company, Compagnie Generale de Geophysique, for work with surface prospecting. He took part in the development of the new telluric, or earth-current method of prospecting and supervised its tests and applications in France, England, Italy, Africa, the United States and Venezuela. Since 1953 he has been in the general research department of the company.

Dr. Kunetz is a member of the European Association of Exploration Geophysicists and the Society of Exploration Geophysicists.

GÉZA KUNETZ



DON R. MABEY

DON R. MABEY received a B.S. degree in physics from the University of Utah in 1951. Since 1951 he has been employed in the Geophysics Branch of the U. S. Geological Survey with headquarters in Salt Lake City, Utah, and Washington, D. C. His principal activities have been in regional geophysical studies in the Great Basin and shallow seismic investigations.

Mr. Mabey is an associate member of the Society of Exploration Geophysicists and the American Geophysical Union.

NORMAN R. PATERSON

NORMAN R. PATERSON was born in 1926 in London, England, and received his early education there, and at Port Hope, Ontario, Canada. He spent the period 1943–1946 in the British Army, serving as a signals officer in England, East Africa and Palestine.

He graduated in the geophysics option of engineering physics from the University of Toronto in 1950, having spent the summers doing field work in gravity, magnetic and electromagnetic prospecting for Radar Exploration Company and Canadian Nickel Company. He received the Master's degree from the University of British Columbia in 1951 with geophysics as his major subject and geology as a minor.

He spent 1951 to 1953 as a seismic interpreter with Imperial Oil Ltd. in Alberta, Canada. In 1953 he returned to the University of Toronto and spent two years conducting research under the physics department in elastic wave propagation in porous media. He received the Ph.D. in 1955.

Since that time he has held the position of manager of geophysical operations with Dominion Gulf Company, Toronto, Canada.

STEPHEN THYSSEN-BORNEMISZA

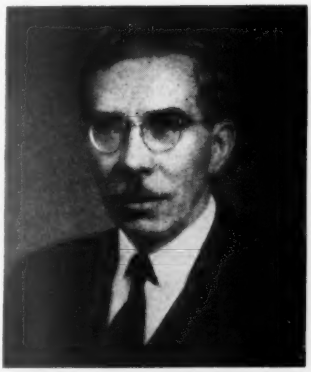
STEPHEN THYSSEN-BORNEMISZA was born near Vienna, Austria in 1907. He studied chemical engineering at M.I.T., chemistry and physics at Zurich University in Switzerland, geophysics at the Eötvös Institute in Budapest receiving his Ph.D. degree in 1932. The same year he entered the Seimos Geophysical Company in Hanover, Germany serving at the torsion balance department. Within 27 years he became president of this company which, under his direction, carried out a large part of the surveys in central and eastern Europe.

He invented the Thyssen-Gravimeter in 1933 which is one of the first gravimeters to be used in the field on a large scale by the Shell Petroleum Co. He is now independent geophysicist in Havana, Cuba.

Dr. St. Thyssen-Bornemisza is a member of the Society of Exploration Geophysicists, of the American Geophysical Union, and life member of the American Association for the Advancement of Science.

DR. W. F. STACKLER, Professional Engineer of Alberta, Canada, is a consulting Geophysicist in Calgary. He received his doctor's diploma in Berlin in 1925 for an isostatic interpretation of a gravity survey in Africa. From 1926 to 1945 he was with Seismos Company in Hannover, in charge of the torsion balance division, and in 1945 became a consultant. In 1952 he moved to Calgary to establish his own practice as a consultant. He is a member of the Society of Exploration Geophysicists, of the European Association of Exploration Geophysicsts, of the American Geophysical Union, of the Alberta Society of Petroleum Geologists and of the Deutsch Geol. Gesellschaft.

W. F. STACKLER



RAOUL VAJK

RAOUL VAJK studied mechanical engineering from 1919 to 1923 at the University of Polytechnics, Budapest, and obtained his Ph.D. degree in geophysics at the University of Science, Budapest. From 1928 to 1931, Dr. Vajk was engaged by the Torsion Balance Exploration Company, Houston, Texas, as geophysical interpreter. From 1933 to 1946, he was head geophysicist of the Hungarian-American Oil Industrial Company (MAORT), Budapest, a Standard Oil Company (New Jersey) subsidiary. In 1939 Dr. Vajk became an associate professor of applied geophysics at the University of Science, Budapest. He published several articles on geophysical problems in various technical periodicals. In October 1946, he immigrated to the United States and has been employed since November 1, 1946, by the Standard Oil Company (New Jersey). He is working in the company's New York office as geophysical advisor.

GEORGE G. WALTON

GEORGE G. WALTON received an A.B. degree in geology from DePauw University in 1933. Since 1934 he has been employed by the Carter Oil Company. He spent some years in foreign work as computer and party chief working in Hungary, Roumania, Peru and France. He is now located in the Carter Tulsa offices as a senior geophysicist.

Mr. Walton is a member of the Geophysical Society of Tulsa and the Society of Exploration Geophysicists.

HARRY WEXLER

HARRY WEXLER is Chief Scientist of the USNC-IGY Antarctic Program and is responsible for its entire scientific effort to be undertaken in 1957 and 1958 in Antarctica. He is a member of the USNC-IGY Antarctic Committee, the USNC-IGY Technical Panel on Meteorology, the ad hoc Arctic Committee and the ad hoc Equatorial Committee. He is also an alternate member of the U. S. National Committee for the International Geophysical Year and its Executive Committee.

Dr. Wexler received his B.S. degree in mathematics from Harvard University in 1932. He did graduate work at the Massachusetts Institute of Technology from 1932 to 1934 and from 1937 to 1938 and obtained his Sc.D. in meteorology in 1939. During the intervening period, 1934 to 1937, he worked at the U. S. Weather Bureau in Chicago, Illinois, and Washington, D. C. He was appointed assistant professor of meteorology at the Institute of Meteorology of the University of Chicago in 1940 and left this position in late 1941 to return to defense work at the Weather Bureau in Washington. In November, 1942, he joined the Army Force's Weather Service as a captain and was appointed senior instructor in meteorology to the Army Air Force Aviation Cadet School in Grand Rapids, Michigan. While there he served as a member of the war-time University Meteorological Committee established to assist the military services in matters related to meteorological training.

In late 1943 Dr. Wexler was transferred to the Weather Division of the Army Air Forces in Washington, where he served as research executive and initiated and fostered a program of research in weather which later developed into the large Air Force program in geophysics. In September, 1944, Dr. Wexler, with Colonel Floyd Wood as pilot, made the first penetration of an Atlantic hurricane, which because of its unusual intensity became known as the "Great Atlantic Hurricane." In 1946 Dr. Wexler became Chief of the U. S. Weather Bureau's Science Services Division. In 1955 he was named Director of Meteorological Research. The Weather Bureau has made Dr. Wexler available to the USNC-IGY for scientific direction of the Antarctic program.

In 1945 the Institute of Aeronautical Sciences presented Dr. Wexler the Losey Award in recognition of his outstanding contributions to the science of meteorology as applied to aeronautics.

Dr. Wexler is a member of the Advisory Committee on Reactor Safeguards for the Atomic Energy Commission, chairman of the Geophysical Research Panel of the Scientific Advisory Board to the Air Force Chief of Staff, and a member of the Meteorological Operations Sub-committee of the National Advisory Committee for Aeronautics. He is vice-president of the American Meteorological Society and a member of the Royal Meteorological Society and the Washington Academy of Sciences. He is a member of the American Geophysical Union and chairman of its Upper Atmosphere Committee. In August, 1955, Dr. Wexler was a member of the U. S. delegation to the "Atoms for Peace" conference in Geneva, Switzerland.

As an internationally recognized authority on meteorology, Dr. Wexler has published some fifty papers in scientific journals treating such subjects as the radiative cooling of the air, polar anti-cyclones, atmospheric turbidity, structure of hurricanes, and upper atmosphere temperatures and dynamic connections with the lower atmosphere.

Dr. Wexler was married in 1934 to the former Hannah Paipert, and they have two daughters, Susan Carol and Libby. They reside in Falls Church, Virginia.

J. E. WHITE

J. E. WHITE received a B.A. degree in 1940 and an M.A. degree in 1946, both from the University of Texas. He received a Ph.D. from the Massachusetts Institute of Technology in 1949. The major subject in each case was physics.

From 1941 to 1945, Dr. White worked on underwater sound problems at the Massachusetts Institute of Technology, serving as director of the MIT Underwater Sound Laboratory during the last year of this period. He then spent one year in guided missiles research at the Defense Research Laboratory in Austin before returning to MIT for graduate work.

From 1949 to 1955, he had charge of a group engaged in geophysical research at the Field Research Laboratories of the Magnolia Petroleum Company. At present he is head of the physics section of the Denver Research Center of The Ohio Oil Company.

Dr. White is a fellow of the Acoustical Society of America and a member of the Society of Exploration Geophysicists, the American Physical Society and the American Association for the Advancement of Science.

ALFRED C. WINTERHALTER

ALFRED C. WINTERHALTER studied chemical engineering at The Rice Institute. He entered the employ of the Sun Oil Company in 1929 as an operator on a refraction seismic crew and later became party chief. He also served as party chief on reflection seismic crews and as research engineer in Sun's geophysical laboratory. At the present time, he is assistant manager of Sun's seismograph department and is in charge of their geophysical research laboratory and shop located at Beaumont, Texas.

He is a member of the Society of Exploration Geophysicists.

ISIDORE ZIETZ

ISIDORE ZIETZ graduated with a B.S. degree in mathematics in 1939 and a Master's degree in 1940 from the College of the City of New York. He is now fulfilling requirements for the Ph.D. in theoretical physics at the Catholic University of America. He was employed by the U. S. Geological Survey as a field topographic engineer in 1941 and has been working with the Survey since that time. He transferred to the Washington, D. C. office in 1942 as a geodetic engineer and served in the U. S. Army from 1944 to 1946 with the 30th Engineers Base Topographic Battalion doing geodetic and topographic work. Upon discharge from the army, he returned to the U. S. Geological Survey as a geodetic engineer. In 1946 he transferred to the Geophysics Branch where he has been working for the most part on research in the interpretation of aeromagnetic data. He was an instructor in mathematics from 1946 to 1950 at Catholic University and is now teaching mathematics part-time at the University of Virginia extension school.

Mr. Zietz is a member of Sigma Xi, the Society of Exploration Geophysics and Geological Society of Washington.

The biography and photograph of Philip L. Lawrence may be found in Geophysics, v. 19, p. 846 (October, 1954).

SOCIETY ROUND TABLE

COMMITTEES FOR THE YEAR ENDING NOVEMBER 1, 1956

Executive Committee

President: R. C. Dunlap, Jr., Geophysical Service Inc., Dallas, Texas
Vice-President: Dave P. Carlton, Humble Oil & Refining Co., Houston, Texas
Secretary-Treasurer: G. A. Grimm, Tide Water Associated Oil Co., Midland, Texas
Editor: Norman Ricker, The Carter Oil Co., Tulsa, Oklahoma
Past President: Paul L. Lyons, Sinclair Oil & Gas Co., Tulsa, Oklahoma

Standing Committees

Nominations

R. C. Dunlap, Jr., *Chairman*
Roy L. Lay
Paul L. Lyons

Tellers

W. M. Erdahl, *Chairman*

Education

Perry Byerly
Beno Gutenberg
John C. Hollister
M. King Hubbert
D. C. Skeels

Student Membership

Fred J. Agnich, *Chairman*
John T. Geer
John C. Hollister
J. Tuzo Wilson

Distinguished Lectures

Peter Dehlinger ('57), *Chairman*
Francis F. Campbell ('56)
John Ferguson ('56)
W. B. Agocs ('57)

Radio Facilities

R. D. Wyckoff, *Chairman*
W. M. Rust, Jr., *Vice-Chairman*
C. B. Bazzoni
Richard Brewer
V. Robert Kerr
E. M. Shook
Daniel Silverman
Bart W. Sorge

Case Histories

D. P. Carlton, *Chairman*
P. L. Lyons, *Editor*
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R. M. Bradley
Norman J. Christie
O. C. Clifford, Jr.
John W. Daly
Milton B. Dobrin
C. H. Dresbach

Membership

H. M. Thralls, *Chairman*
John E. McGee
Bart W. Sorge

Honors and Awards

Andrew Gilmour ('56), *Chairman*
George E. Wagoner ('57)
Sigmund Hammer ('58)
Curtis H. Johnson ('59)
Roy L. Lay ('60)

Publications

John P. Woods, *Chairman*
Cecil H. Green
Sigmund Hammer
L. L. Nettleton
H. B. Peacock

Reviews

W. T. Born, *Chairman*
Kumiji Iida
F. K. Levin
Daniel Linehan, S.J.
L. M. Mott-Smith
R. G. Piety
Frank Press
Luigi Solaini

Publicity

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G. A. Burton
John Byers
G. M. Conklin
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Sigmund Hammer
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P. M. Konkel
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H. V. Crowder
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Russell L. Long
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Thomas S. West

Public Relations

Bart W. Sorge, *Chairman*
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Eugene Frowe
F. O. Mortlock
Ralph B. Ross

Geophysical Activity

H. G. Patrick, *Chairman*
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R. J. Copeland
Santos Figueroa Huerta
W. W. Hardy
Herbert Hoover, Jr.
C. N. Hurry
Kumiji Iida
C. C. Lister

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Walter Jasper
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G. M. Kintz
Frank Searcy
Bart W. Sorge
R. A. Weisbrich
Marvin Romberg
E. S. Sherar
Dean Walling

Mining Case Histories

Harold O. Seigel, *Chairman*
J. Ewart Blanchard
Kenneth L. Cook
Sherwin F. Kelly
Howard McMurry
Robert G. Van Nostrand

Constitution and Bylaws

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Andrew Gilmour
Cecil H. Green
Sigmund Hammer
J. J. Jakosky
L. L. Nettleton

Committee on American Institute of Physics

Norman Ricker, *Chairman*
C. B. Bazzoni
D. H. Clewell
Maurice Ewing
L. Y. Faust
Sigmund Hammer
D. S. Hughes
L. B. Slichter

Research

D. H. Clewell, *Chairman*
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J. M. Crawford
C. Hewitt Dix
H. F. Dunlap
Maurice Ewing
C. H. Green
B. D. Lee
L. L. Nettleton
T. J. O'Donnell
R. A. Peterson
Daniel Silverman
P. S. Williams

Index of Wells

V. U. Gaither, *Chairman*

Magnetic Recording

R. R. Thompson, *Chairman*
Keith R. Beeman
Roland F. Beers
K. E. Burg
J. D. Eisler
Glenn M. Grosjean
J. E. Hawkins
K. M. Lawrence
B. D. Lee
A. J. W. Novak
R. A. Peterson
F. A. Van Melle

Subcommittee on Definitions & Measurement

R. A. Arnett
L. B. McManis
Frank Coker
L. W. Erath
J. M. Cunningham
J. J. Durapau
F. J. Feagin
H. R. Frank
Roger Harlan
R. W. Kelley
R. C. Moody

Subcommittee on Recorder Characteristics

S. Kaufman, *Chairman*
A. L. Parrack
J. D. Skelton

AAPG-SEG-SEPM Committee on Radioactive Mineral Exploration (SEG members)

Henry C. Cortes, *Vice-Chairman*
Roland F. Beers
Cecil H. Green
Gerhard Herzog
Gerald H. Westby

American Geological Institute Directors

Roy L. Lay ('56)
Paul L. Lyons ('57)

National Research Council Div'n of Earth Sciences Representative

C. B. Bazzoni

AAAS Council Representative

Roland F. Beers

LOCAL SECTIONS

GEOPHYSICAL SOCIETY OF TULSA

(Chartered February 2, 1948)

President: Wm. M. Erdahl, Skelly Oil Co.
1st Vice-President: John J. Rupnik, Rupnik and Ballou
2nd Vice-President: James J. Johnson, Sinclair Oil & Gas Co.
Secretary: Ralph D. Lynn, The Carter Oil Co.
Treasurer: John E. Bondurant, Phillips Petroleum Co.
Editor: V. L. Jones, Consultant
District Representatives:
H. M. Thralls ('56), Geo Prospectors, Inc.
W. T. Born ('56), Geophysical Research Corp.
L. Y. Faust ('57), Amerada Petroleum Corp.
Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, Room 224, Petroleum Science Hall

SOCIETY OF EXPLORATION GEOPHYSICISTS HOUSTON SECTION

(Chartered February 14, 1948)

President: W. Harlan Taylor, Taylor Exploration Co.
1st Vice-President: J. F. Freel, Research Exploration, Inc.
2nd Vice-President: John Byers, States Explorations Co.

Secretary: S. Brooks Stewart, Sohio Petroleum Co.
Treasurer: M. L. Benke, Oil Reserves Corp.
District Representatives:
O. B. Hocker ('56), The Texas Co.
W. T. Lea ('57), Cities Service Oil Co.
Meetings: Monthly, Noon luncheon ($1.50), Rice Hotel.

PACIFIC COAST SECTION

(Chartered April 12, 1948)

President: T. P. Ellsworth, Geophysical Service Inc., Bakersfield, Calif.
Vice-President Northern District: Paul F. Clement, Western Gulf Oil Co., Bakersfield, Calif.
Vice-President Southern District: Lawrence K. Morris, Union Oil Co. of Calif., Los Angeles
Secretary-Treasurer: Thomas A. Roy, The Ohio Oil Co., Bakersfield, Calif.
District Representatives:
Flint H. Agee, United Geophysical Corp. Arcadia, Calif.
William D. Cortright, Tide Water Assoc. Oil Co., Bakersfield
Joseph C. Waterman, Shell Oil Co., Los Angeles

DALLAS GEOPHYSICAL SOCIETY

(Chartered August 7, 1948)

President: John A. Lester, Magnolia Petroleum Co.
1st Vice-President: H. F. Dunlap, The Atlantic Refining Co.
2nd Vice-President: Glenn M. Conklin, Sun Oil Co.
Secretary-Treasurer: M. S. Hathaway, The Atlantic Refining Co.
District Representatives:
Martin C. Kelsey, Rayflex Exploration Co.
C. G. Dahm, Hunt Oil Company
Meetings: Monthly, generally but not invariably 2nd Monday (contact any member). 8:00 P.M. Fondren Science Bldg., S.M.U.

FORT WORTH GEOPHYSICAL SOCIETY

(Chartered August 7, 1948)

President: H. E. Itten, Empire Geophysical Inc.
Vice-President: Richard Brewer, Continental Geophysical Co.
Secretary-Treasurer: Carl Wert, Gulf Oil Corp.
District Representatives:
Frank Mortlock, Gulf Oil Corp.
L. O. Seaman, Sinclair Oil and Gas Co.
Meetings: Monthly, 4th Monday, Noon Luncheons ($1.50), Texas Hotel.

ARK-LA-TEX GEOPHYSICAL SOCIETY

(Chartered March 12, 1949)

President: Herbert J. Ferber
Vice-President: Charles Bragg
Secretary-Treasurer: H. L. Grant
District Representatives:
Jackson Young
B. B. Burroughs, Sunray Oil Corp.
Meetings: Monthly, normally last Monday, Noon Luncheon ($1.50), Captain Shreve Hotel, Shreveport.

PERMIAN BASIN GEOPHYSICAL SOCIETY

(CHARTERED JANUARY 30, 1950)

President: DECKER DAWSON, Dawson Geophysical Co.
1st Vice-President: MAXEY PINSON, Union Oil Co. of California
2nd Vice-President: W. A. SEAL, JR., Continental Geophysical Co.
Secretary: MALCOLM KNOCK, Stanolind Oil and Gas Co.
Treasurer: R. J. KNOTT, The Atlantic Refining Co.
District Representatives:
L. H. JOHNSON, Honolulu Oil Corp.
C. N. PAGE, Continental Geophysical Co.
LORENZ SHOCK, Midland Geophysical Co.
Meetings: Monthly, 2nd Tuesday 7:30 P.M., free coffee and doughnuts, Midland Womens Club, Midland, Texas

DENVER GEOPHYSICAL SOCIETY

(CHARTERED MAY 19, 1950)

President: E. B. WASSON, Cosden Petroleum Co.
Vice-President: C. E. RIDDELL, Consultant
Secretary-Treasurer: J. E. THOMPSON, Sun Oil Co.
District Representative: C. C. O'BOYLE, Brainerd & Van Tuyl
Meetings: Monthly, 1st Monday, 5:30 P.M., meeting only, Petroleum Club.

CANADIAN SOCIETY OF EXPLORATION GEOPHYSICISTS

(CHARTERED JANUARY 24, 1952)

President: R. B. ROSS, Canadian Gulf Oil Co.
Vice-President: G. J. BLUNDUN, Home Oil Co.
Secretary-Treasurer: DON V. BIGELOW, Mobil Oil of Canada, Ltd.
District Representatives:
G. F. COOTE, Accurate Exploration Ltd.
F. A. HALE, Calif. Standard Co.
Meetings: Monthly Evening Meetings—No Set Schedule.

GEOPHYSICAL SOCIETY OF OKLAHOMA CITY

(CHARTERED SEPTEMBER 30, 1952)

President: R. D. ROBERTS, Sohio Petroleum Co.
1st Vice-President: JOHN BEMROSE, Sohio Petroleum Co.
2nd Vice-President: D. D. MOORE, Seismic Explorations, Inc.
Secretary: GEORGE E. ANDERSON, Stanolind Oil & Gas Co.
Treasurer: Ben W. Smith, Continental Oil Co.
District Representative: R. D. ROBERTS, Sohio Petroleum Co.
Meetings: Monthly, 2nd or 3rd Monday, time and place to be announced.

CASPER GEOPHYSICAL SOCIETY

(CHARTERED MAY 23, 1953)

President: H. F. FARMER, Richfield Oil Corp.
Vice-President: H. F. DODSON, The Atlantic Refining Co.
Secretary-Treasurer: C. M. BROWN, Teton Tool Co.
District Representative: Homer Roberts, Petty Geophysical Engineering Co.
Meetings: Monthly, 1st Monday, 7:00 P.M., Dinner ($2.75), Townsend Hotel

GEOPHYSICAL SOCIETY OF SOUTH TEXAS

(CHARTERED NOVEMBER 9, 1953)

President: W. LEE MOORE, Petty Geophysical Engineering Co.
Vice-President: WILLIAM R. GRAY, Consulting Geologist
Secretary-Treasurer: DILLON S. FRAZIER, Petty Geophysical Engineering Co.
District Representative: WELDON L. CRAWFORD, Petty Geophysical Engineering Co.
Meetings: Semi-monthly, 1st and 3rd Wednesdays, Noon luncheon (Cafeteria style), Sommers Cafeteria, Main Plaza, San Antonio.

SOUTHEASTERN GEOPHYSICAL SOCIETY

(CHARTERED APRIL 1, 1954)

President: JOHN F. BOYD, Tidelands Exploration Co., New Orleans
Vice-President: O. G. HOLEKAMP, Shell Oil Co., New Orleans
Secretary-Treasurer: R. E. HALSEY, Sinclair Oil & Gas Co., New Orleans
District Representatives:
L. W. COBENA, The Texas Co., New Orleans
M. G. FREY, The California Co., New Orleans
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans

MONTANA GEOPHYSICAL SOCIETY

(CHARTERED APRIL 12, 1954)

President: SAM MARSH, The Carter Oil Co.
1st Vice-President: JACK PETERS, Mobil Producing Co.
2nd Vice-President: M. D. WICKERHAM, Gulf Oil Corp..
Secretary-Treasurer: C. F. MOORE, Sohio Petroleum Co.
District Representative: THOMAS C. KING, Murphy Corp.
Meetings: Monthly, Second Monday, 7:30 P.M., Billings Petroleum Club, Billings.

DAKOTA GEOPHYSICAL SOCIETY

President: W. E. PHILLIPS, Stanolind Oil & Gas Co., Box 1437, Bismarck, N. D.
1st Vice-President: HUGH MCCAIN, The Atlantic Refining Co., Box 1076, Bismarck, N. D.
2nd Vice-President: QUIN HAYES, Mobil Producing Co., Box 1236, Bismarck, N. D.
Secretary-Treasurer: R. R. PHAIR, Roundup Powder Co., Box 452, Bismarck, N. D.
District Representative: HENRY NOGAMI, The Atlantic Refining Co., Box 728, Dickinson, North Dakota
Meetings: Monthly, 1st Friday, 7:30 P.M., Petroleum Club, Prince Hotel, Bismarck.

JACKSON GEOPHYSICAL SOCIETY

(CHARTERED MAY 12, 1955)

President: FRED FORWARD, Phillips Petroleum Co.
Vice-President: W. J. ROBINSON, Sinclair Oil & Gas Co.
Secretary-Treasurer: R. LONG, Stanolind Oil & Gas Co.
District Representative: J. W. GREEN, Donnally Exploration Co.
Meetings: Monthly, during third week, 5:30–6:30 refreshments, 6:30–7:30 dinner ($2.00), technical meeting to follow, Roof Garden of Robert E. Lee Hotel, Jackson, Mississippi.

SOUTHWEST LOUISIANA GEOPHYSICAL SOCIETY

Lafayette, Louisiana

(CHARTERED JANUARY 4, 1956)

President: J. J. SCHNEIDER, JR., Sohio Petroleum Co , Box 1090, Lafayette, La.
1st Vice-President: E. L. RICKETTS, Forest Oil Corp., Box 1401, Oil Center Sta., Lafayette, La.

2nd Vice-President: E. L. CURRENT, Cities Service Oil Co., Box 1407, Oil Center Sta., Lafayette, La.
Secretary-Treasurer: J. W. BELL, JR., Pan-Amer. Prod. Co., Drawer 1409, Oil Center Sta., Lafayette, La.
District Representatives:
E. L. RICKETTS, Forest Oil Corp.
P. H. JEFFERS, Chemical Service Inc.

STUDENT SOCIETIES

(AFFILIATED)

COLORADO SCHOOL OF MINES SOCIETY OF STUDENT GEOPHYSICISTS

Golden, Colorado

President: RONALD E. DIEDERICH
Vice-President: ROGER C. GORE
Secretary-Treasurer: ROBERT I. BUCKNELL
Faculty Sponsor: JOHN C. HOLLISTER
Meetings: (Data not received)

GEOPHYSICAL SOCIETY OF SAINT LOUIS UNIVERSITY

President: RICHARD SNEIDER
Vice-President: GILBERT BOLLINGER
Secretary: THOMAS MCEVILLY
Treasurer: ROBERT RILEY

Faculty Moderator: (To be appointed)

Meetings: Monthly, 2nd Wednesday, 7:30 P.M., Meeting only, Institute of Technology.

SOCIETY OF EXPLORATION GEOPHYSICISTS HOUSTON STUDENT SECTION

President: TOM VINING, University of Houston
1st Vice-President: D. E. MILLER, Rice Institute
2nd Vice-President: EUGENE GREEN, University of Houston
Treasurer: JACK WRIGHT, University of Houston
Secretary: D. H. COOK, University of Houston
University of Houston Sponsor: DR. R. A. GEYER, Geophysical Service Inc., Box 6937, Houston 5, Texas
Rice Institute Sponsor: DR. CHARLES B. OFFICER, JR.
Meetings: (Data not received)

UNIVERSITY OF TORONTO GEOPHYSICAL SOCIETY

President: DOUGLAS W. ALLAN
Vice-President: JOHN JAMIESON
Secretary-Treasurer: JOHN E. HOGG
Faculty Sponsor: PROF. J. A. JACOBS
Meetings: Bi-weekly, alternate Thursdays, 4:00 P.M., 49 St. George St.

UNIVERSITY OF TULSA STUDENT GEOPHYSICAL SOCIETY

Dept. of Geophysics
600 S. College, Tulsa, Oklahoma

President: SCOTT SMITH
Vice-President: JUAN SUAREZ
Secretary-Treasurer: PAT DOBY
Faculty Sponsor: PROF. H. M. ZENOR
Meetings: Weekly, Thursday, 11:00 A.M., 116 Petroleum Science Bldg., Campus.

TRANS-PECOS STUDENT SECTION

Box 56, Texas Western College
El Paso, Texas

President: JOE H. SCALES
1st Vice-President: PETER G. GRAY
2nd Vice-President: HARRY R. HIRSCH
Secretary: JOHN T. SAMPLE, JR.
Treasurer: WILLIAM D. GRANT
Faculty Sponsor: WM. S. STRAIN
Meetings: To be announced.

PENNSYLVANIA STATE UNIVERSITY GEOPHYSICAL SOCIETY

College of Mineral Industries
University Park, Pennsylvania

President: JOHN K. LYON — *Secretary:* JAMES B. IMSWILER
Vice-President: HAROLD G. ROZELLE — *Treasurer:* DONALD W. STRICKLER
Faculty Sponsor: DR. B. F. HOWELL

UNIVERSITY OF UTAH GEOPHYSICAL SOCIETY

College of Mines and Mineral Industries
Salt Lake City, Utah

President: WILLIAM M. DOLAN — *Secretary:* HOWARD L. CONFER
Vice-President: J. BURLIN JOHNSON, JR. — *Treasurer:* PETER MANDEL, JR.
Faculty Advisor: DR. KENNETH L. COOK
Meetings: Monthly, 1st Thursday, noon, Mines Bldg.; other special meetings to be announced

GEORGIA INSTITUTE OF TECHNOLOGY GEOPHYSICAL SOCIETY

Box 4748
Atlanta, Georgia

President: CLIFFORD N. CHANCEY, JR. — *Secretary-Treasurer:* WILLIAM HOGARTH
Vice-President: JACK GRAVENMIER — *Faculty Sponsor:* DR. H. W. STRALEY III

MEMBERSHIP APPLICATIONS RECEIVED

Applications for Active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the President within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

John F. Boyd (J. B. Ferguson, R. R. Moore, R. L. Palmer, R. G. St. Germain)
George Castellucci (C. H. Johnson, Robert Dyk, H. L. Rasé, Robert Dundon)
C. M. Chappell (E. R. Brumbaugh, J. M. Nash, F. R. Veasaw, R. C. Kendall)
C. R. Church (H. G. Patrick, D. P. Carlton, Glenn E. Bader, Wm. M. Rust, Jr.)
E. H. Clark (A. L. Ladner, H. M. Thralls, Roy Bennett, W. B. Brinnon)
Robert J. David (R. C. Dunlap, Jr., F. J. Agnich, Cecil H. Green)
C. A. Dittrich (R. F. Keller, Jack Martin, T. O. Hall)
J. H. Edge (A. P. Wendler, W. M. Burney, J. J. Flowers, D. B. Moore)
S. H. Figueroa (R. F. Aldredge, Vladimir Olhovich, Daniel Gutierrez, Jesus Basurto)
David J. Flesh (Robert Baum, R. M. Wilson, Rolla T. Wade, Glenn Baker, W. Barrett)
Paul H. Foster (Norman Ricker, H. J. Wirz, R. D. Lynn, W. A. Alexander)
A. Frey (R. A. Weisbrich, H. L. Brewer, A. Farando, J. J. Holtzscherer)
E. A. Fulmer (F. A. Hale, C. M. Moore, Jr., A. W. Farmilo, Phil P. Gaby)
M. J. Goodspeed (R. F. Thyer, K. R. Vale, E. J. Polak, J. A. Hakes)
Robert Halvorsen (R. H. Carlyle, R. Copeland, A. H. McKee, H. J. McGrew)
W. G. Hatlelid (A. P. Crosby, C. J. Chapman, A. S. Gibson)
John R. Henderson, Jr. (James R. Balsley, H. R. Joesting, Roland G. Henderson, Isidore Zietz)
M. C. Hester (A. G. Nance, A. L. Barnes, E. A. Pratt, D. P. Melton)
Raymond F. Holsch (C. A. Weeth, H. V. Goss, F. H. McGowan)
D. Henao L. (R. M. Tesar, Harry M. Imle, L. G. Morales, T. B. Portwood)
A. Helmer (H. H. Brons, B. Baars, O. Koefoed)
M. R. Hundley (F. R. Kittredge, Leland Snow, P. M. McNally, F. M. Hawpe)

C. E. Hutchings (H. F. Dodson, A. E. McKay, R. D. Arnett, J. D. Divelbiss)
J. H. Jackson, Jr. (R. A. Boulware, C. L. Hart, W. H. Johnson, J. H. Frasher)
Charles A. Kehoe (Ben F. Rummerfield, Neal Clayton, A. A. Brant, C. B. Reed)
C. L. Kendrick (C. H. Broussard, C. P. Harkins, R. C. Wilber, R. T. Penny)
C. R. Krampitz (C. P. Harkins, G. H. Harrington, A. W. Bunsen, N. N. Zirbel)
Marc Lepetit (Paul Giraud, Claude Aynard, Lucien Beaufort)
H. A. Lukowitch (C. C. Brooks, L. D. Ervin, A. L. Ballou)
Orville G. Lundstrom (V. A. Peterson, James M. Wilson, John F. Anderson, A. G. Nance)
J. B. Mantez (Paul Giraud, Claude Aynard, René Bouchon)
Russell B. Maurer (Frank E. Ittner, Dale E. Turner, Jack Martin, N. W. Engel)
L. K. Monk (E. C. Livingston, C. H. Hightower, E. L. DeLoach, O. C. Clifford)
J. J. Needham (R. J. Copeland, R. H. Carlyle, A. A. Lee, R. B. Ross)
Carl C. Palmer (R. R. Thompson, Wm. M. Rust, Jr., D. H. Gardner, D. P. Carlton)
D. H. Parry (L. R. Lipsett, D. K. McIvor, R. E. Pallat, C. H. Acheson)
L. A. Peterson (T. S. Green, C. C. Williams, R. D. Arnett, E. L. Campbell)
John Rempel (G. C. Agnew, J. B. Murphy, A. P. Crosby)
D. P. Robertson (O. Koefoed, B. Baars, C. J. Velzeboer, D. M. Balmforth)
William Roever (Lorenz Shock, H. F. Dodson, F. A. VanMelle, G. W. Postma)
R. Rousseau (Paul Giraud, Claude Aynard, Lucien Beaufort)
B. J. Seaman (M. E. Baker, Ted Rozsa, W. N. Rabey)
G. D. Sindorf (A. A. Hunzicker, B. H. Hinton, K. A. Webb, D. D. Moore)
Victor W. Smith (H. D. McGrady, V. E. Prestine, Dean Walling, Henry Salvatori)
W. L. D. Smith (H. J. Kidder, D. V. Bigelow, L. Castelli, K. C. Coulter)
Luther B. Stevens (O. C. Clifford, J. P. Woods, C. H. Hightower)
D. J. Studebaker, (B. O. Winkler, N. B. Sauvé, J. I. Walton, R. L. Craig)
Robert J. Switz (W. W. LaRue, F. M. Hawpe, C. P. Durant, G. W. McCoy)
Robert W. Teipel (Stefan Von Croy, R. W. Mossman, H. M. Thralls, T. S. Green)
J. M. Vallet (Paul Giraud, Claude Aynard, Fernand Blondy)
Harry S. Whitcomb, Jr. (A. A. Hunzicker, Hugh Porter, Jr., T. E. Hobbs, G. G. Vanderdoes)
Lyle T. White (E. R. Locke, C. C. Zimmerman, M. L. Benke)
E. N. Wright (J. L. Burns, I. C. Mayfield, J. H. Bush, H. M. Smith)
Hunter Yarborough (D. P. Carlton, H. G. Patrick, Wm. M. Rust, Jr., C. S. Fleischman)

APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

Warren A. Alexander (Norman Ricker, A. B. Bryan, Marvin Romberg)
Nigel A. Anstey (E. J. P. van der Linden, J. E. Hawkins, A. A. Fitch)
William E. Bonini (George P. Woollard, Sam P. Worden)
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TWENTY-SIXTH ANNUAL MEETING

The 26th Annual Meeting of the Society of Exploration Geophysicists will be held October 29 through November 1, 1956 at the Roosevelt Hotel, New Orleans, Louisiana. Kenneth R. Wells, General Chairman, has announced that the program will feature world-wide offshore exploration, and arrangements are being made for the "field trip" to include observations of geophysical operations in the Gulf of Mexico.

Under the chairmanship of O. G. Holekamp, the technical program is being assembled by the program chairmen of the respective local sections. The new International Room of the Roosevelt Hotel provides space for sixty-six commercial exhibit booths, representing an increase of eighteen booths. Another feature will be a student interview service being planned by the SEG Student Membership Committee.

In addition to K. R. Wells and O. G. Holekamp, the following committee chairmen have been appointed: C. W. Penny, General Vice-Chairman; J. A. Harris, Exhibits; E. H. Shannon, Housing; Merrill Smith, Finance; John F. Boyd, Registration and Reception; Neil W. Mann, Arrangements; G. A. Burton, Publicity; D. D. Utterback, Entertainment; George Morgan, Field Trip; R. E. Halsey, Program Publication; and Mrs. John F. Boyd, Ladies Program.

Hotel accommodations in New Orleans are expected to be adequate, and a number of rooms have been assigned to SEG for this meeting. These rooms will be reserved only for applications submitted on the official reservations form which has been mailed to all members in good standing. Because double rooms outnumber singles, delegates are requested to share accommodations. Additional reservation forms may be obtained from the SEG Business Office.

AMENDMENTS TO CONSTITUTION AND BYLAWS

During its annual meeting on October 5, 1955, the Council instructed the Special Committee on Constitution and Bylaws to recommend amendments which would provide for the following:

1. Increase the annual dues as follows: For Active grade, $10.00 per year. For Associate grade, $8.50 per year for a period of five years and $10.00 per year thereafter. Dues for Student grade would remain $4.50 per year.
2. Status as standing committees for the Research Committee and the Special Business Office Committee.
3. Election of District Representatives by a larger portion of the membership, providing representation on the Council for more members.

In accordance with these instructions the committee has recommended the following amendments to the Constitution:

Amend Article XII of the Constitution as follows: Change the title from "Districts" to "Representatives-at-Large."

Cancel the present Sections 1 and 2.

Add a new Section 1: "The number of Representatives-at-Large shall be specified in the Bylaws but shall not be less than three."

Add a new Section 2: "Representatives-at-Large shall be elected from among the Honorary Members and Active Members of the Society in good standing for terms stated and in the manner prescribed in the Bylaws and shall not be eligible for two consecutive terms."

Add a new Section 3: "Representatives-at-Large shall have all the rights and authority of District Representatives."

The committee has recommended the following amendments to the Bylaws:

Amend Article VII by adding at the end of the first sentence of Section 2 the words "including Representatives-at-Large."

Amend Section 5 by adding at the end of the first sentence the words "including District Representatives and Representatives-at-Large."

In Section 7 after the words "for each officer" add the words "and for either the indicated number of Representatives-at-Large or of District Representatives from a single local Section."

Amend Article VIII by deleting the first sentence of Section 6 and adding at the end of Section 6 the sentence "The Local Section shall nominate in the manner prescribed by its Bylaws of nominating section officers, two candidates for each District Representative to be elected and submit their names to the President of the Society prior to June 1."

Delete the present Section 7 and add a new Section 7: "The number of Representatives-at-Large shall be be three. The term of office of a Representative-at-Large shall be two years, except that one of the Representatives-at-Large elected in 1957 shall serve a single year."

Amend Article IV, Section 2, as follows: Delete "or Associate." Delete "seven dollars and fifty cents ($7.50)" and substitute "ten dollars ($10)." Add "The annual dues of an Associate Member of the Society shall be eight dollars and fifty cents ($8.50) for a period of five years and ten dollars ($10) thereafter, which includes the cost of one subscription to the Society's journal."

Amend Article X of the Bylaws by adding at the end of Section 1: "(o) Standing Committee on Research; and (p) Standing Committee on Business Office."

Add Section 17: "The Standing Committee on Research shall consist of a chairman, appointed for one year by the President, and such additional members, appointed by the chairman, as he may deem desirable. The committee shall recommend policy with regard to research and shall carry out projects to promote research in geophysics."

Add Section 18: "The Standing Committee on Business Office shall consist of a chairman, appointed for one year by the President, and such additional members, appointed by the chairman, as he may deem desirable. The committee shall advise the business manager and shall maintain a procedure manual."

This publication of proposed amendments to the Constitution is done in accordance with Article XVIII of the Constitution as published in GEOPHYSICS, v. 20, n. 4, p. 988 (October, 1955), and of proposed amendments to the Bylaws in accordance with Article XVII of the Constitution as published on page 987 in the same issue.

ANNOUNCEMENTS

ANNUAL STUDENT ESSAY CONTEST

The third annual Student Essay Contest has been announced by the Society of Exploration Geophysicists.

The contest, which is held to stimulate interest in the field of exploration geophysics among university students, is open to all undergraduate students currently enrolled in at least one course in geophysics. Membership in a student chapter of the SEG is not a prerequisite.

Three cash prizes will be awarded. First place receives $150; second, $100; third, $50. All winners will also receive certificates suitable for framing, and the winning paper may be published in GEOPHYSICS.

Subjects should be chosen from the field of exploration geophysics or earth physics. Papers must represent a worthwhile contribution to the literature of geophysics, and should be the entrants' own work, not a compilation or digest of previously published papers. Subjects might be: a new

nstrument, technique, method or theory in geophysics, or a previously undescribed case history. There is no restriction to treatment. Papers may be scientific expositions or discussions of economic or philosophic aspects of the subject.

Closing date for entries is October 1, 1956. Winners will be announced at the annual meeting of the Society in New Orleans, Louisiana, October 29–November 1, 1956. Entires should be addressed to: F. J. Agnich, Student Essay Contest, Geophysical Sercv ieInc., 5900 Lemmon Avenue, Dallas 9, Texas.

DENVER SECTION RECEIVES SLIDE PROJECTOR

Smiles of pride (and relief) greeted the presentation of a slide projector by SEG to the Denver Geophysical Society in appreciation of the fine way in which the Denver Section planned and carried out the Twenty-fifth Anniversary Meeting. Robert Dyk, General Chairman of the meeting (left) clasps the hand of E. B. Wasson, President of the Denver society, as he makes the presentation. Looking on are (left to right) J. E. Thompson, C. E. Riddell, C. C. O'Boyle and Ralph C. Holmer.

THE MAYHEW SCHOLARSHIP IN GEOPHYSICS

The scholarship program of the Society of Exploration Geophysicists was inaugurated March 8, 1956, with the announcement by President R. C. Dunlap, Jr., of the Mayhew Scholarship in Geophysics. Funds for the award were to be granted by the Mayhew Supply Company, Inc., of Dallas, Texas. The award of $3,000.00, providing $750.00 per year for four years toward tuition and other expenses, will be made annually to the son or daughter of a person engaged in geophysical work and employed by a geophysical company, geophysical branch of an oil company, or a contract drilling company. Only high school seniors or graduates will be eligible.

Announcement of the program was mailed to all SEG members last April. June 1, 1956, was the deadline for applications this year.

CIVIL SERVICE EXAMINATIONS ANNOUNCED

The United States Civil Service Commission has announced an examination for filling Geophysicist positions in the Coast and Geodetic Survey of the Department of Commerce, and other Federal agencies in Washington, D. C., and throughout the United States. A few positions may also be filled overseas. The salaries range from $4,345 to $11,610 a year.

Appropriate education and experience are required. For positions paying from $4,345 to $5,440 a year, education alone may be qualifying. No written test is required.

Further information and application forms may be obtained at many post offices throughout the country, or from the U. S. Civil Service Commission, Washington 25, D. C. Applications will be accepted by the Board of U. S. Civil Service Examiners, Coast and Geodetic Survey, Department of Commerce, Washington 25, D. C., until further notice.

SEG BUSINESS OFFICE MOVED TO AAPG BUILDING

On March 30, 1956, the Business Office of the Society was moved to spacious new quarters on the ground floor of the AAPG Building in Tulsa. A total of 1,400 square feet of space was partitioned especially to suit the needs of the SEG staff, and a five-year lease has been signed. Up-to-date in every respect, the new offices are arranged for the efficiency needed to keep up with the rapid growth of the Society.

The new street address is 107 West Fifteenth Street. The mailing address will remain Box 1536, Tulsa 1, Oklahoma.

PERSONAL ITEMS

Members of the Society are invited to notify the business manager of any changes in their positions or companies for announcement in this section. Members are further invited to check with the public relations departments of their companies to assure that the Society is on their mailing lists to receive publicity releases.

ROBERT B. RICE has been appointed senior research physicist in the physics section of The Ohio Oil Company's research center under construction in Denver, Colorado.

JERRY NELSON, of Farmingdale, New York, an Associate Member of SEG, was killed in an airplane crash at Dover, Delaware, Monday, February 20, 1956.

LEONARD K. BULLER has been named field supervisor for Southern Geophysical Company's Houston office.

OTIS B. HOCKER, division manager of The Texas Company's geophysical division, advises that the geophysical operations of the company's producing department in Texas have merited first place in Group II (100 to 499 employes—160,000 or more hours) of the Industrial Safety Contest for 1955, sponsored by the Texas Safety Association.

HELENITA OFFICER ROSAY, whose address is 788 Ridgeside Drive, Monrovia, California, advises she would like to sell the following issues of GEOPHYSICS: v. 8, no. 1; v. 11, nos. 2, 3, & 4; v. 12, nos. 1, 2, 3, 4; v. 13, nos. 2 & 4; v. 18, nos. 1, 2, 3 & 4; and v. 19, nos. 1 & 2.

A multi-million dollar plan for the future development of the COLORADO SCHOOL OF MINES was announced February 17, 1956 when Dr. John W. Vanderwilt, president of the college, told over 150 Colorado civic, state, and industrial leaders the story of the school's "Horizon Plan" at a special dinner held at the University Club.

Supplementing his talk with a booklet outlining the "Horizon Plan" in detail, President Vanderwilt cited goals of over $20,000,000 in capital funds and $450,000 in annual funds to augment state support by the school's centennial year in 1974.

While paying tribute to the State of Colorado for its backing in the past and expressing con-

fidence in continued state support in the future, the Mines president pointed out that supplementary non-state funds will be needed if the college is to meet its obligations as the nation's primary source of mineral engineers.

Included in the "Horizon Plan" is $850,000 for a geophysics building.

Billings Geological Society will hold its Seventh Annual Field Conference August 16–18, 1956, in the Big Snowy Mountains area of the Central Montana uplift. Reservation and Pre-registration application forms may be secured from C. R. Hammond, Box 1504, Billings, Montana.

Alberta Society of Petroleum Geologists will hold its Sixth Annual Field Conference August 23–25, 1956 in the area between Calgary and Banff, centering in the Canmore—Kananaskis region. For particulars write to the society at Box 141, Calgary, Alberta, Canada.

PETER C. BADGLEY recently resigned as exploration manager of West Maygill Gas & Oil Ltd., Calgary, Alberta, to join the geology faculty at the Colorado School of Mines, Golden. Dr. Badgley will continue in an advisory capacity with West Maygill.

AERO SERVICE CORPORATION of Philadelphia has presented a copy of its fascinating relief map of the United States to the SEG. This plastic map measures 64 inches by 40 inches, is self-framed and lithographed in eleven colors. It is a useful and attractive addition to the new quarters of the Business Office on the ground floor of the AAPG Building in Tulsa.

L. L. HAMMIAL has resigned as review geophysicist for Houston Oil Company to join the staff of PAUL FARREN, geophysical consultant. The consulting firm occupies new offices in the Bank of the Southwest, Houston, Texas.

JAMES E. BERRY and WARREN G. HICKS, members of the Magnolia Petroleum Company's Field Research Laboratories, have been promoted to Senior Research Technologists. Mr. Berry, a research geophysicist, is a project leader engaged in research on problems of interpretation of logging methods. Mr. Hicks is a research engineer whose present assignment is a study of the application and evaluation of continuous velocity logging in exploration and production problems.

JACK L. MATAYA has been named district geophysicist at Stanolind Oil and Gas Company's district office at Tyler, Texas. He will supervise geophysical activities of Stanolind's East Texas and Abilene districts. Prior to his promotion, he was a staff geophysicist in Tyler.

CALENDAR OF MEETINGS

1956

September

5–13 Theoretical and Applied Mechanics, 9th International Congress, IUTAM, Brussels, Belgium. (H. L. Dryden, 1512 H Street, N.W., Washington 25, D. C.)

17–21 International Congress on Theoretical Physics, IUPAP, University of Washington, Seattle. (J. H. Manley, University of Washington, Seattle, Washington)

October

1– 3 National Electronics Conference, Hotel Sherman, Chicago, Illinois

18–20 Optical Society of America, Lake Placid Club, Essex County, New York (S. S. Ballard, Scripps Institute of Oceanography, San Diego 25, California)

28– 1 Society of Exploration Geophysicists, 26th Annual Meeting, Roosevelt Hotel, New Orleans, Louisiana (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

November

12–15 American Petroleum Institute, 36th Annual Meeting, Conrad Hilton Hotel, Chicago, Illinois

15–17 Acoustical Society of America, Los Angeles, California (W. Waterfall, 57 E. 55th Street, New York 22, New York)

23–24 American Physical Society, Chicago, Illinois (K. K. Darrow, Columbia University, New York 27, New York)

1957

February

24–28 AIME Annual Meeting, Roosevelt Hotel, New Orleans, Louisiana

April

1– 4 American Association of Petroleum Geologists 42nd Annual Meeting—and Society of Economic Paleontologists and Mineralogists 31st Annual Meeting, Kiel Auditorium and Jefferson Hotel, St. Louis, Missouri (E. W. Ellsworth, Box 979, Tulsa, Oklahoma)

November

10–15 Society of Exploration Geophysicists 27th Annual Meeting, Statler-Hilton Hotel, Dallas, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

July 1, 1957 to December 31, 1958

International Geophysical Year. (Worldwide) vide GEOPHYSICS, v. 21, p. 257–259. and v. 21, p. 681–690.

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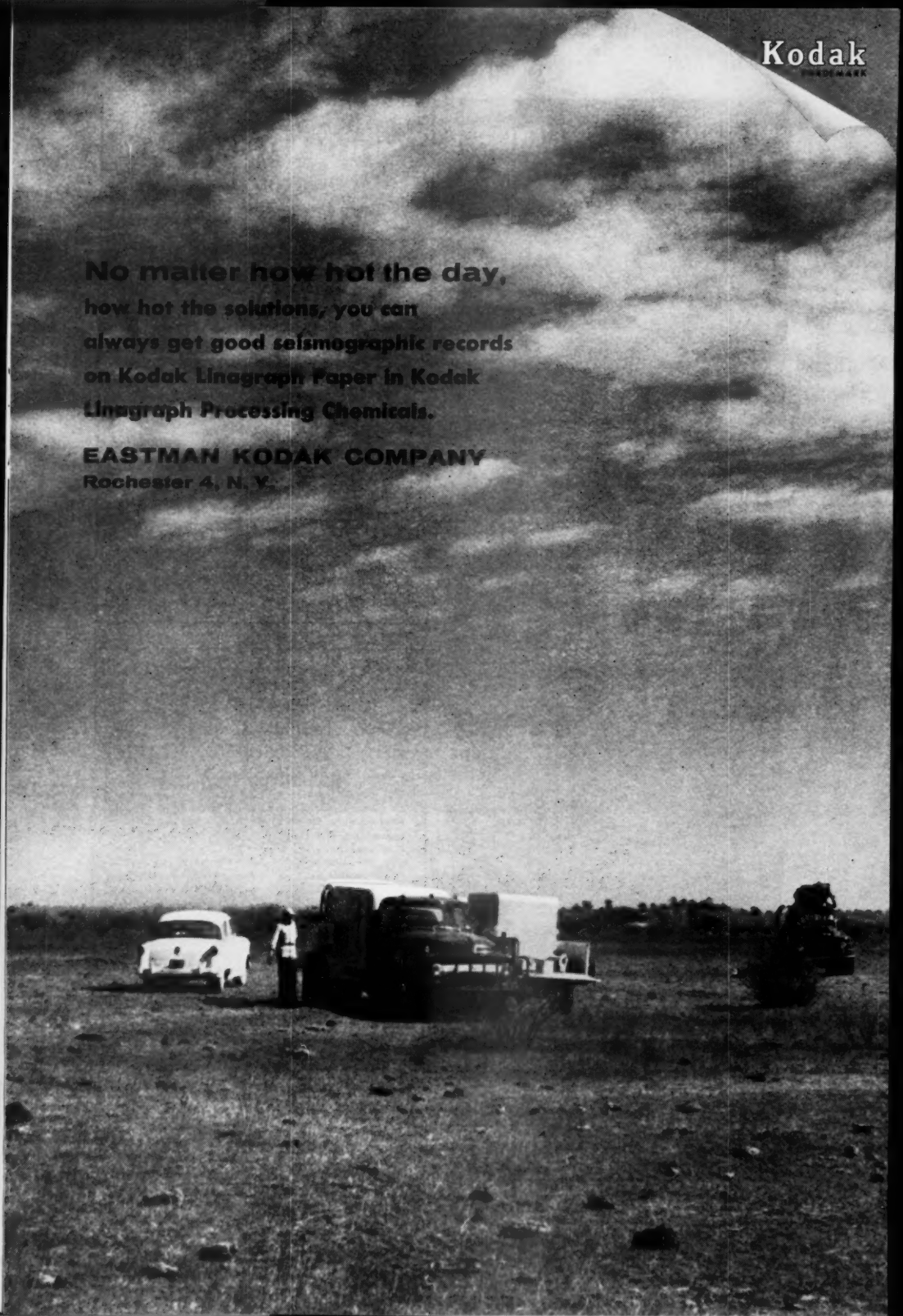
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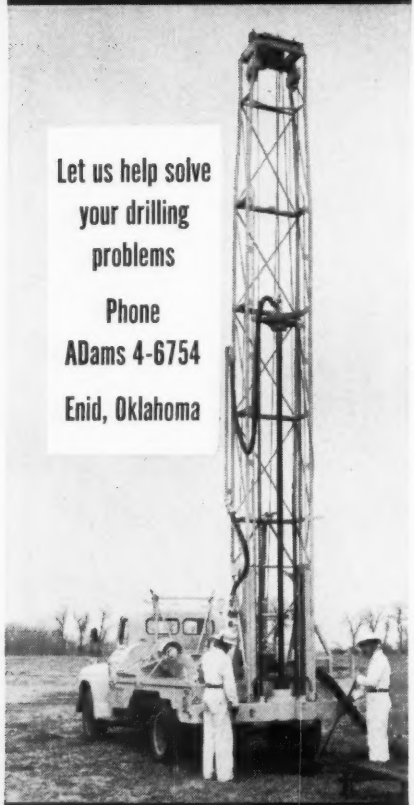

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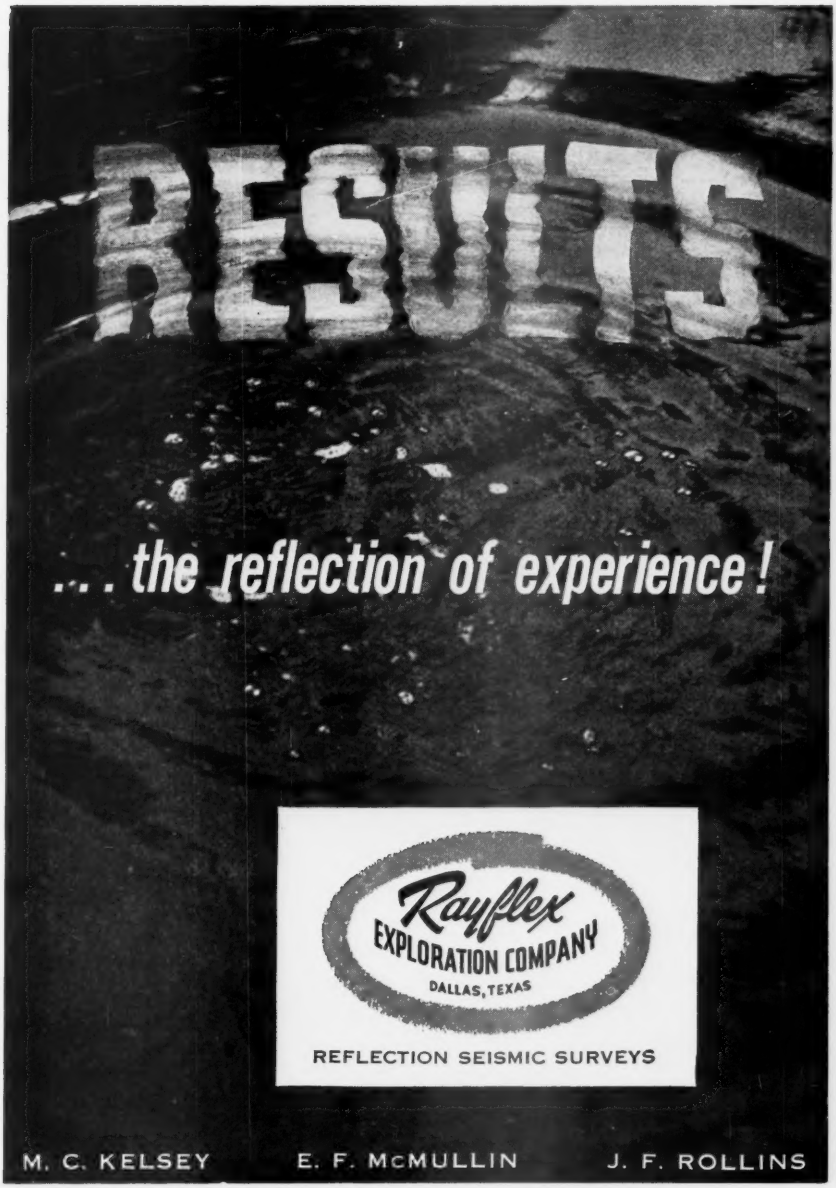
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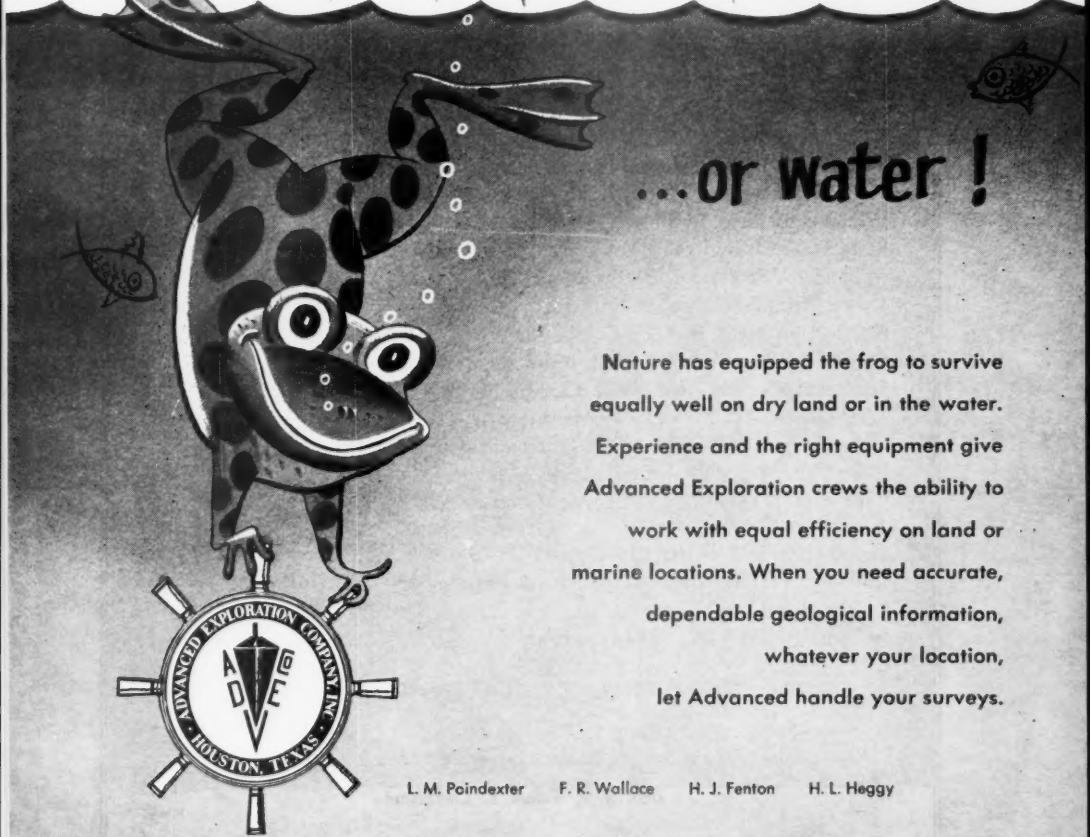

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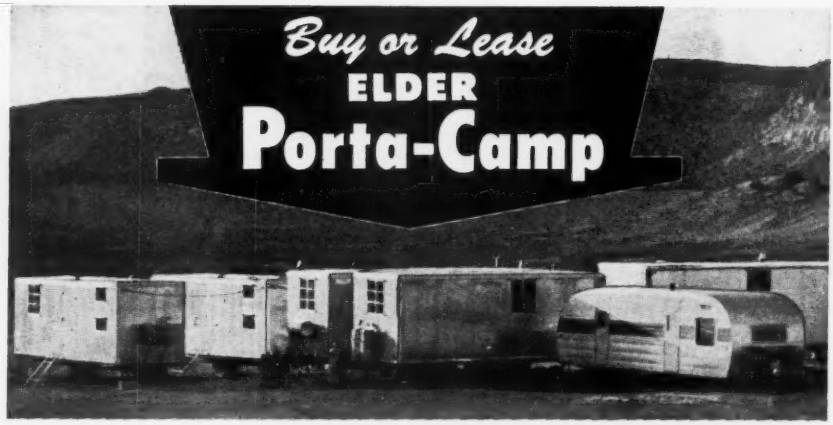

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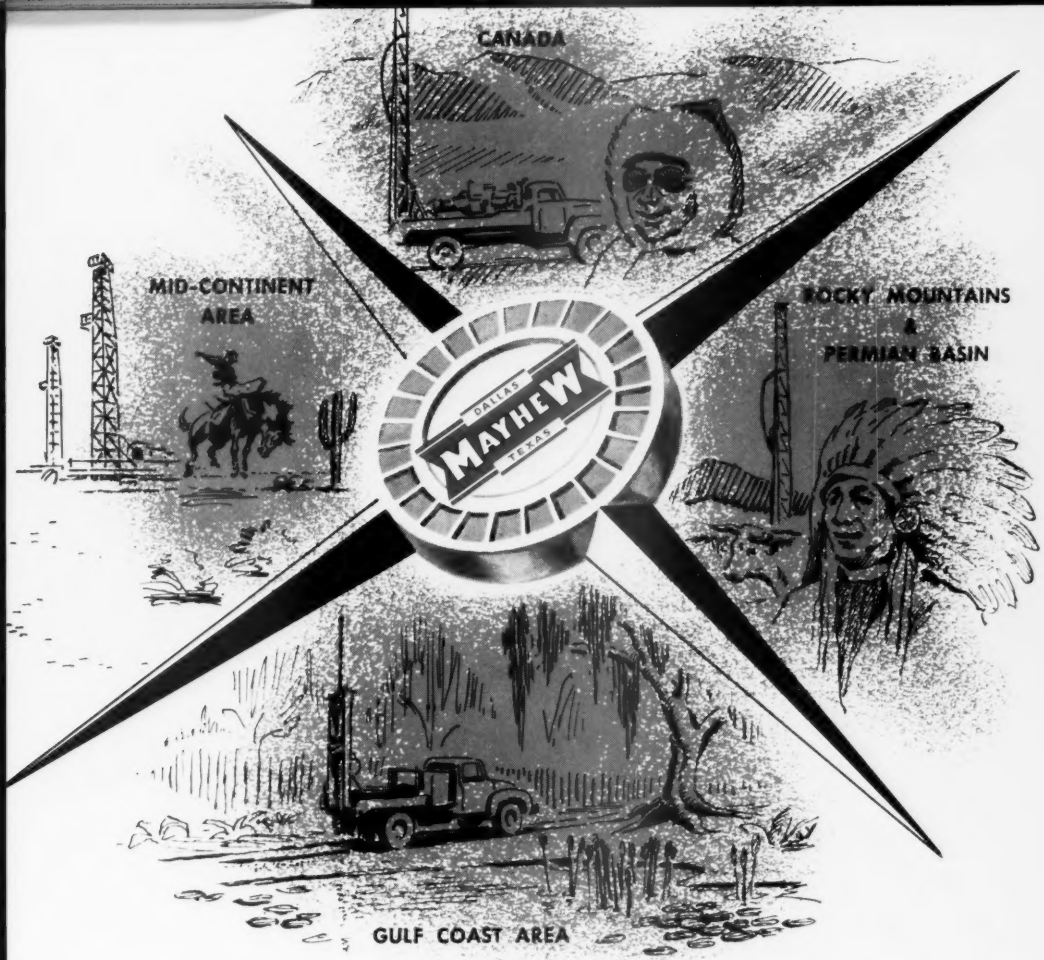

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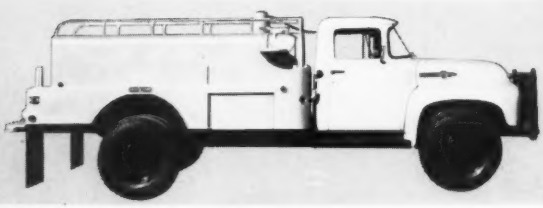

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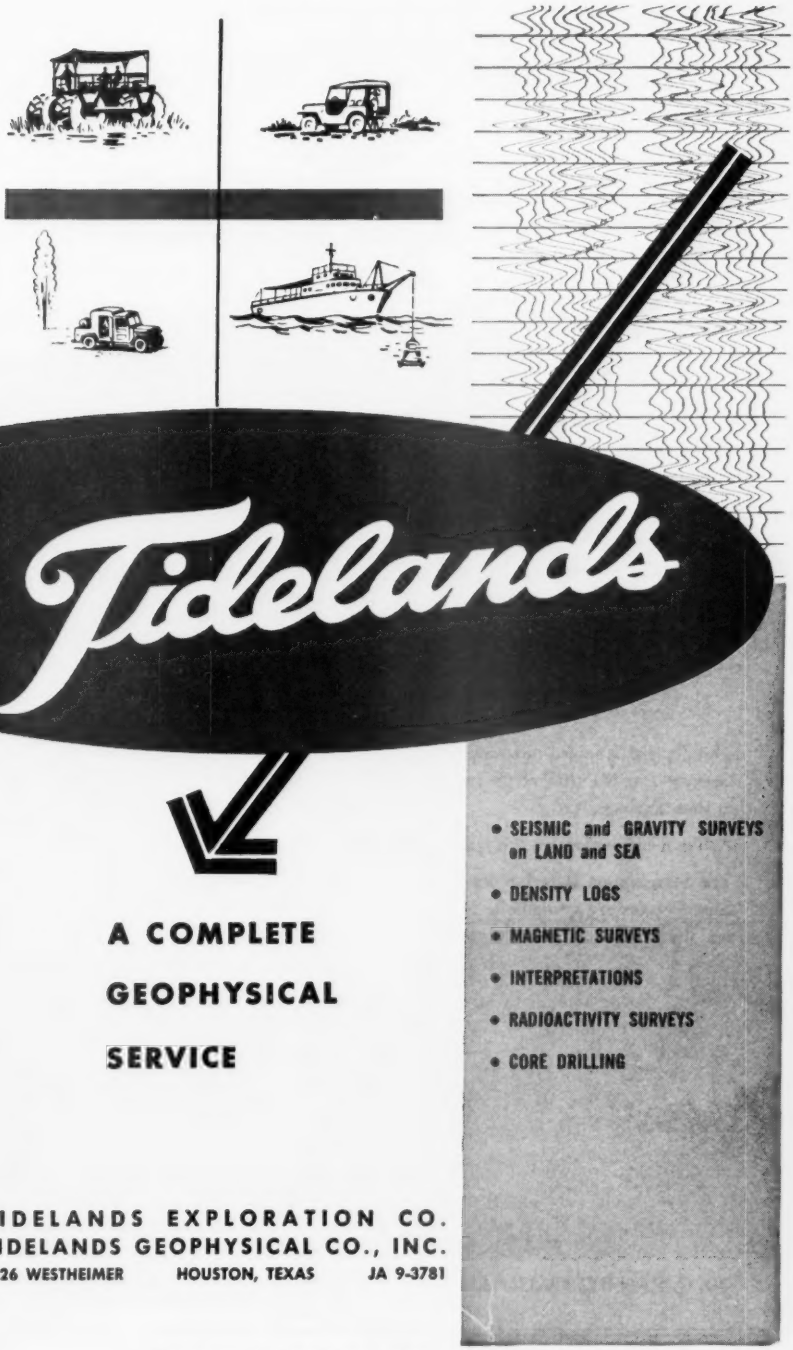
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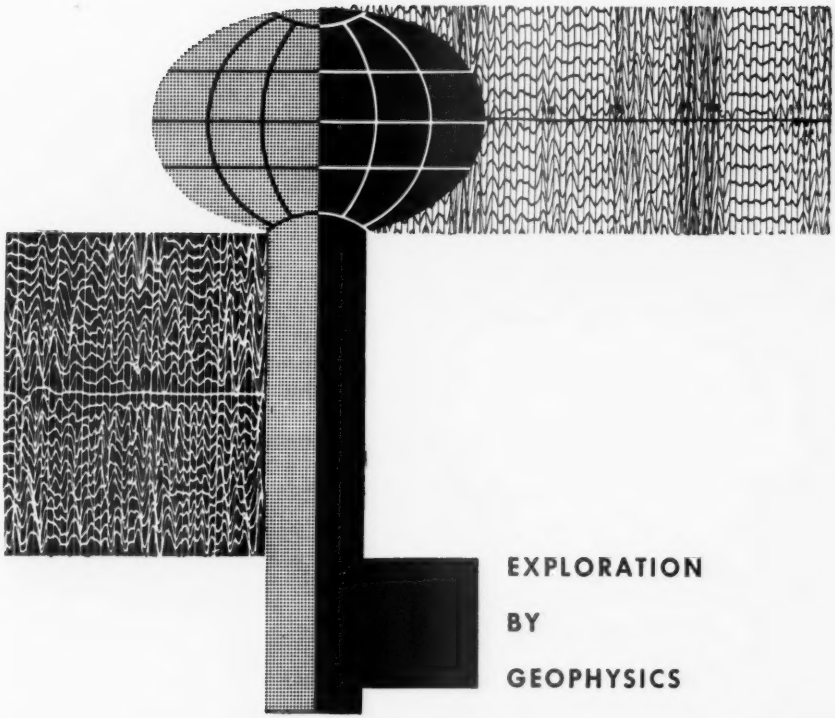

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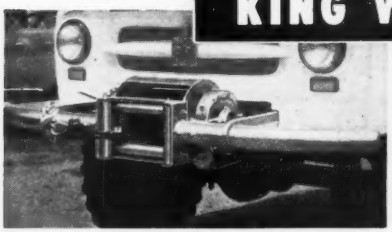

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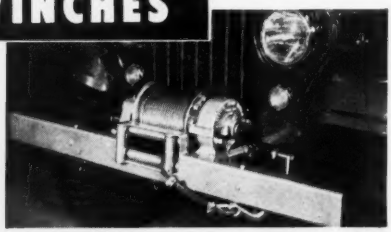

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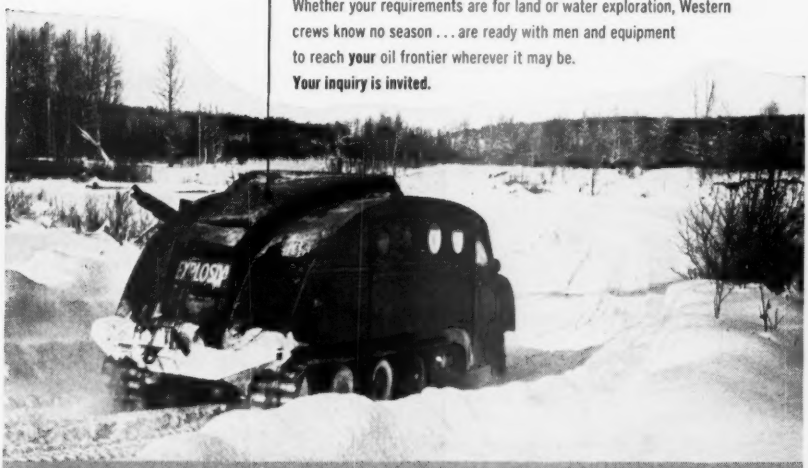

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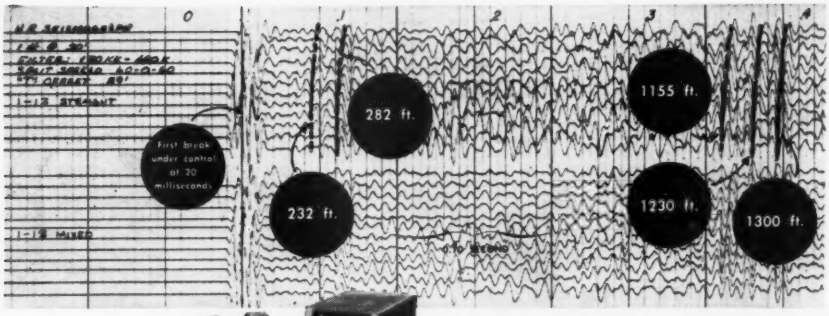

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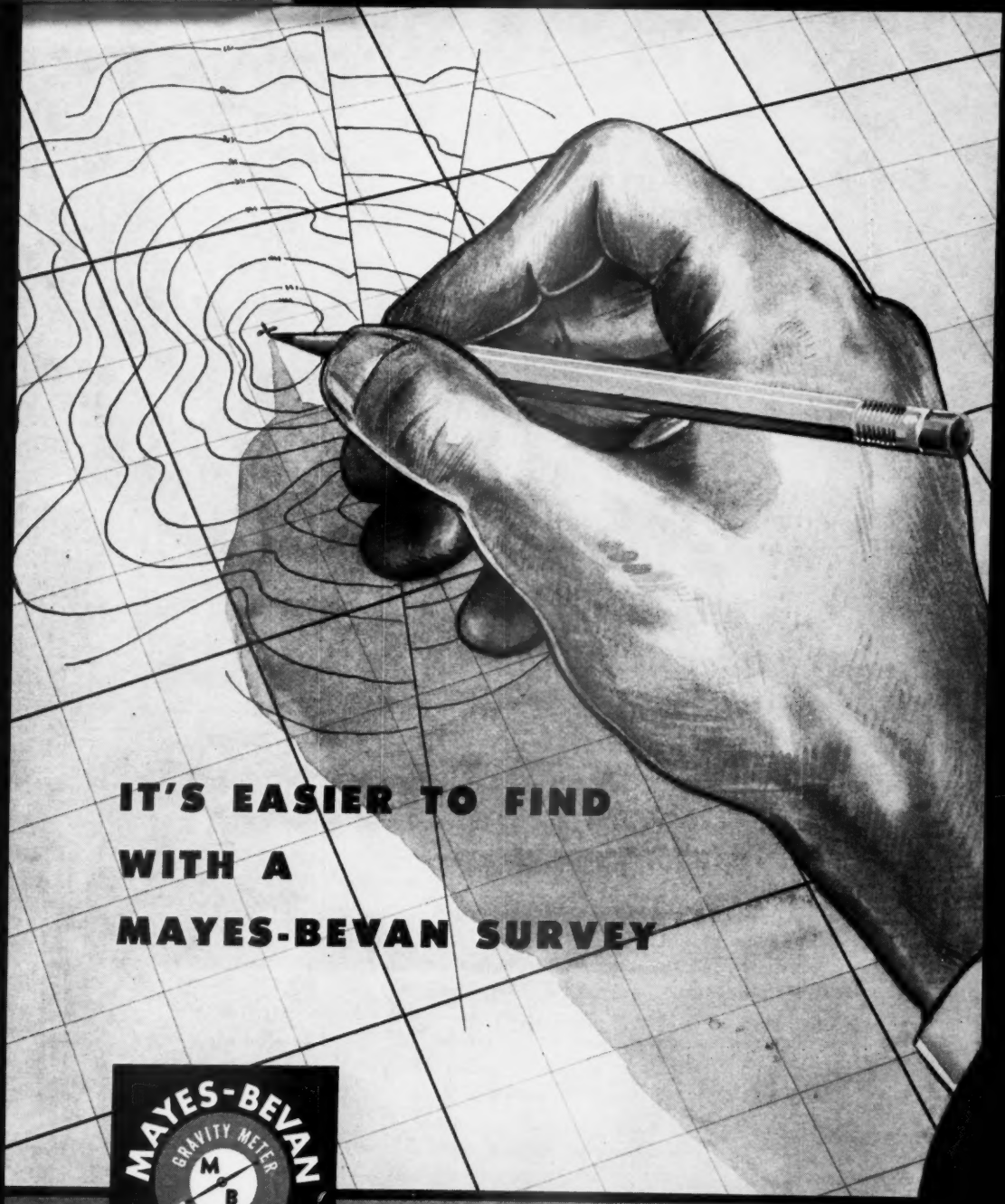

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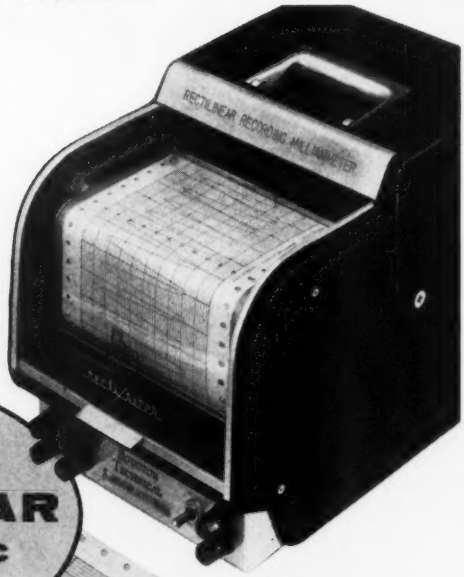

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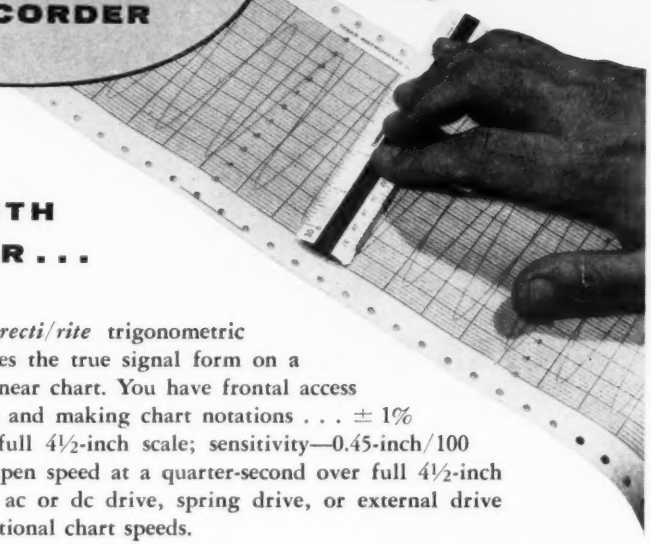

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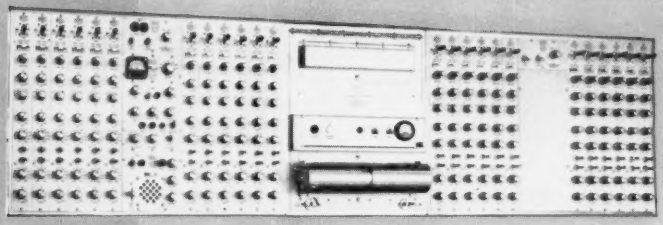

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The GA-33 Geophysical Amplifier features Full-Spectrum filtering, variable AGC time-constants, and extremely low distortion (less than 1%). Its wide range is especially useful in magnetic recording applications, while plug-in construction permits simple installation and easy maintenance.

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SOUTHWESTERN INDUSTRIAL ELECTRONICS CO.

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221 - 55

MAGNETIC RECORDING SYSTEMS

The impact of magnetically recorded wide-band seismic information has been met at SIE by the most intensive research and development program in the company's history. Co-operating with geophysicists and engineers active in every phase of petroleum and electronic instrumentation, SIE has evolved the MR series of magnetic recorders together with auxiliary equipment and two new wide-band seismograph systems, the G-22A, and G-33. In addition, custom designed magnetic recording equipment has been produced to meet special requirements of several large geophysical organizations.

In magnetic recording instrumentation as in conventional seismograph manufacture SIE equipment continues to set,

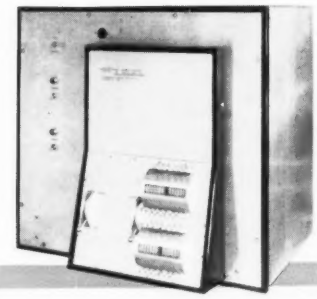
The Standard of the Industry

MR-4 MAGNETIC RECORDER

. . . features outstanding versatility and reliability. Signal-to-noise ratio in excess of 60 db, wide frequency range, and extremely low distortion suit the MR-4 for every field recording application.

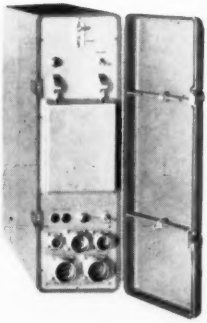
MR-5 MAGNETIC RECORDER

. . . can be used for more complex field recording, and is especially useful in laboratory analysis. Twin tape transport and individual head positioning controls allow recordings to be composited for noise integration and other interpretation techniques.



PMR-6 PORTABLE MAGNETIC RECORDER

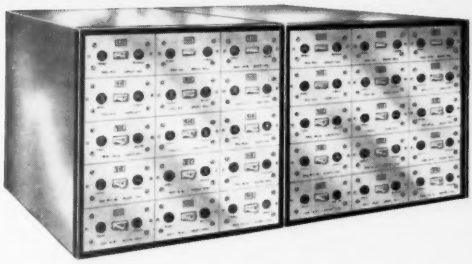
. . . can be used in areas completely inaccessible to vehicle mounted systems. Weighing only 43 pounds, the PMR-6 uses the same recording tape as the MR-4 and MR-5 and is easily carried by one man.



and LABORATORY ANALYSIS SYSTEMS

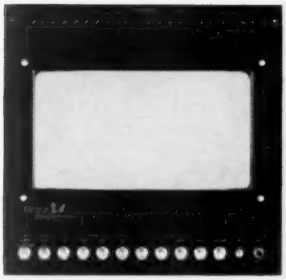
SIE auxiliary equipment for magnetic recording includes specially designed units and modifications for various field and laboratory techniques. Direct viewing equipment which allows records to be examined in the field with MR-4 and MR-5 Recorders, is one example. Recorders are available with or without frequency modulation equipment; the noise reducing SIE Length-Time Servo System; and moveable recording heads, thus permitting the selection of a system tailor made for every application at lower cost.

In the laboratory, the SIE Normal Move-Out Remover is one example of the specialized analysis equipment available. Development and research on other magnetic recording devices is a continuous process at SIE. When planning any phase of a wide-band instrumentation program, be sure to call for information on the latest SIE developments.



MODULATOR—DEMODULATORS

. . . for frequency modulation recording are housed in two cases for vehicle installation. Using the SIE Slope Modulator which provides an extremely high deviation ratio, the Units feature very low distortion—less than 1%.



MO MULTI-CHANNEL OSCILLOSCOPE

. . . allows laboratory presentation of an entire magnetic recording. Twenty-four channels are portrayed with timing lines, thus permitting records to be examined rapidly during interpretation and when compositing and filtering.

SERVICE INTEGRITY EXPERIENCE

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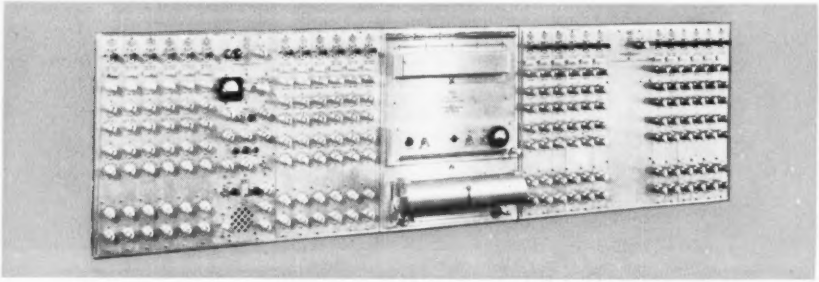
G-22A

SEISMOGRAPH SYSTEM



for high-production Operations

FREQUENCY RESPONSE: Within 3 db from 10 to 500 cps. Filtering as specified.

LOW DISTORTION: Less than 1% from 10 to 500 cps at 0.1 volt input.

AGC CONTROL RANGE: 0.5 microvolt to 0.1 volt input. (Three time-constants selected from front panel.)

GAIN CONTROL CIRCUITS: AGC, Expander, or simultaneous AGC-Expander operation.

RECORD PRESENTATION: Single record. Dual output. Dual record.

- First-Arrivals Unfiltered.
- Individual Channel Paralleling and Testing Switches.
- Simplified Controls.

Features essential to high-speed operation — available only on special order in many systems — are standard equipment in the G-22A.

New circuitry provides unmatched performance with all recording methods while simplifying matching and operating procedures.

AGC Time-Constants, mixing method and percentage, and type of record presentation can be selected from the front panel. Two attenuation rates on both high and low cut filters provide hundreds of filtering combinations.

From the new self-biased AGC circuit to the simplified control panel, the G-22A's "field engineered" design combines practical operation with high flexibility.

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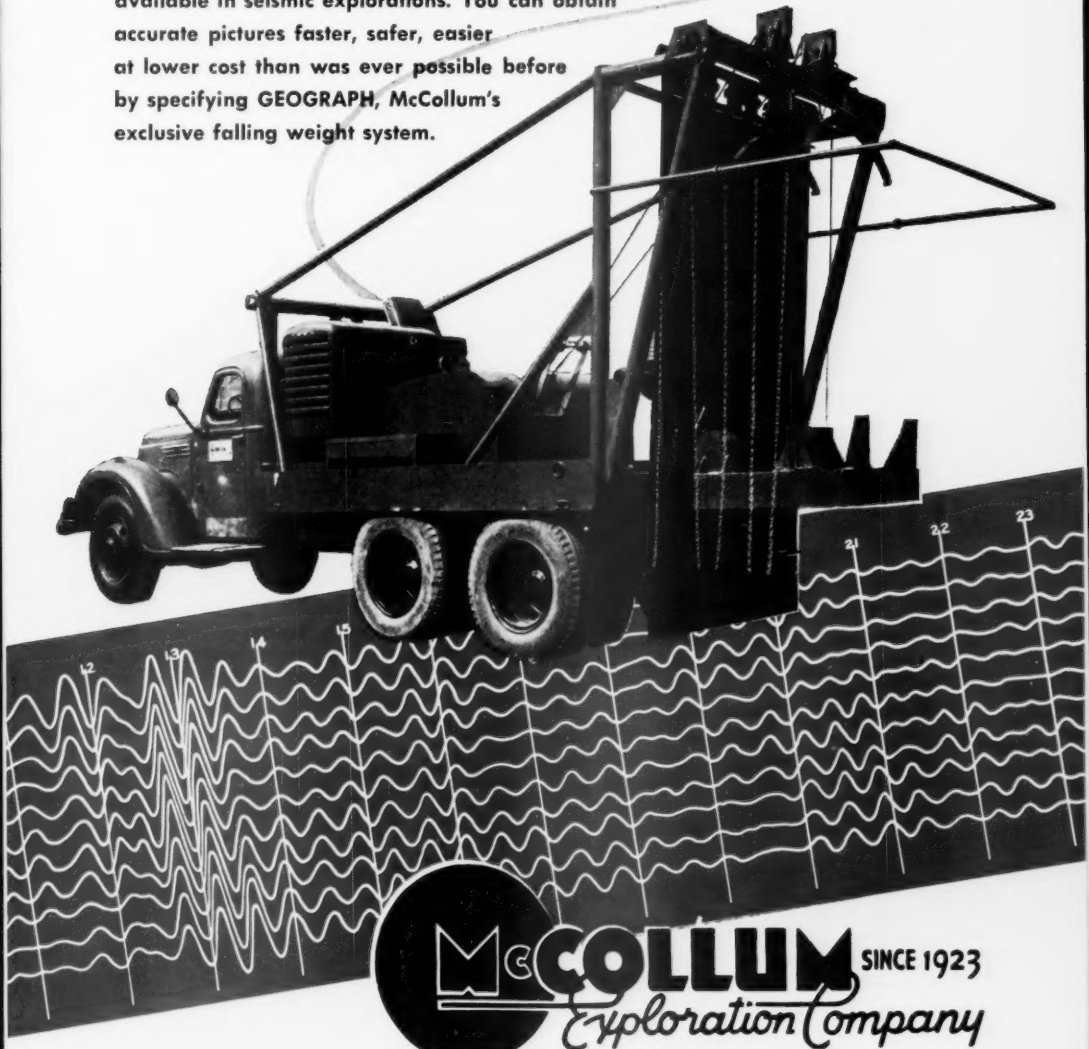

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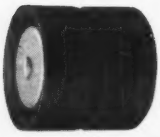
MacCLATCHIE GEOPHYSICAL PUMP PARTS!

For the fluid end of your small size geophysical pumps, here's a quick line-up of MacClatchie replacement parts *engineered* to give you maximum dependable service under the tough conditions of exploration work . . .

MacClatchie Type "GS" Pump Piston



—for general field service in all makes and sizes of pumps and for all rod tapers. Lip design of rubbers allows expansion under fluid pressure, insuring leak-proof operation. Piston easily renewed by replacing worn rubbers, using end plates and center spool over again.

MacClatchie Type "FR" Pump Piston—A *one-piece* piston with *no metal* to touch the liner bore . . . no end plates . . . no lock rings . . . no separate body. The best piston available at an economy price—made in most popular sizes and rod tapers.

MacClatchie Type "GS" Wing Guide Valve

—Engineered with full opening value seat to permit free flow of cuttings, heavy slurries and foreign material without sticking. Easily disassembled to replace worn insert by removing single cap screw.

MacClatchie Geo-Mac Valve—For Geophysical Service

—This all new Geo-Mac Valve has no inserts to replace, no snap rings or lock plates—just a pressure plate which you attach to the valve body with a nut and bolt. The special hardened pressure plate takes no wear, therefore lasts indefinitely. Made of revolutionary new "Permac" rubber compound, the Geo-Mac withstands the toughest geophysical service and *is giving unparalleled performance.*

MacClatchie Liners and Rods—MacClatchie one-piece hardened and honed liners are made from steel forgings, scientifically heat treated and mirror-honed. O.D. is machined for perfect fit. Chrome plated liners also available.

MacClatchie Rods are made in all API and manufacturer's tapers of carburized and hardened alloy steel, ground to a smooth finish to prevent scoring and corrosion. Also available chrome plated. Furnished complete with rod and jam nut.

Write for Descriptive Literature and Specifications

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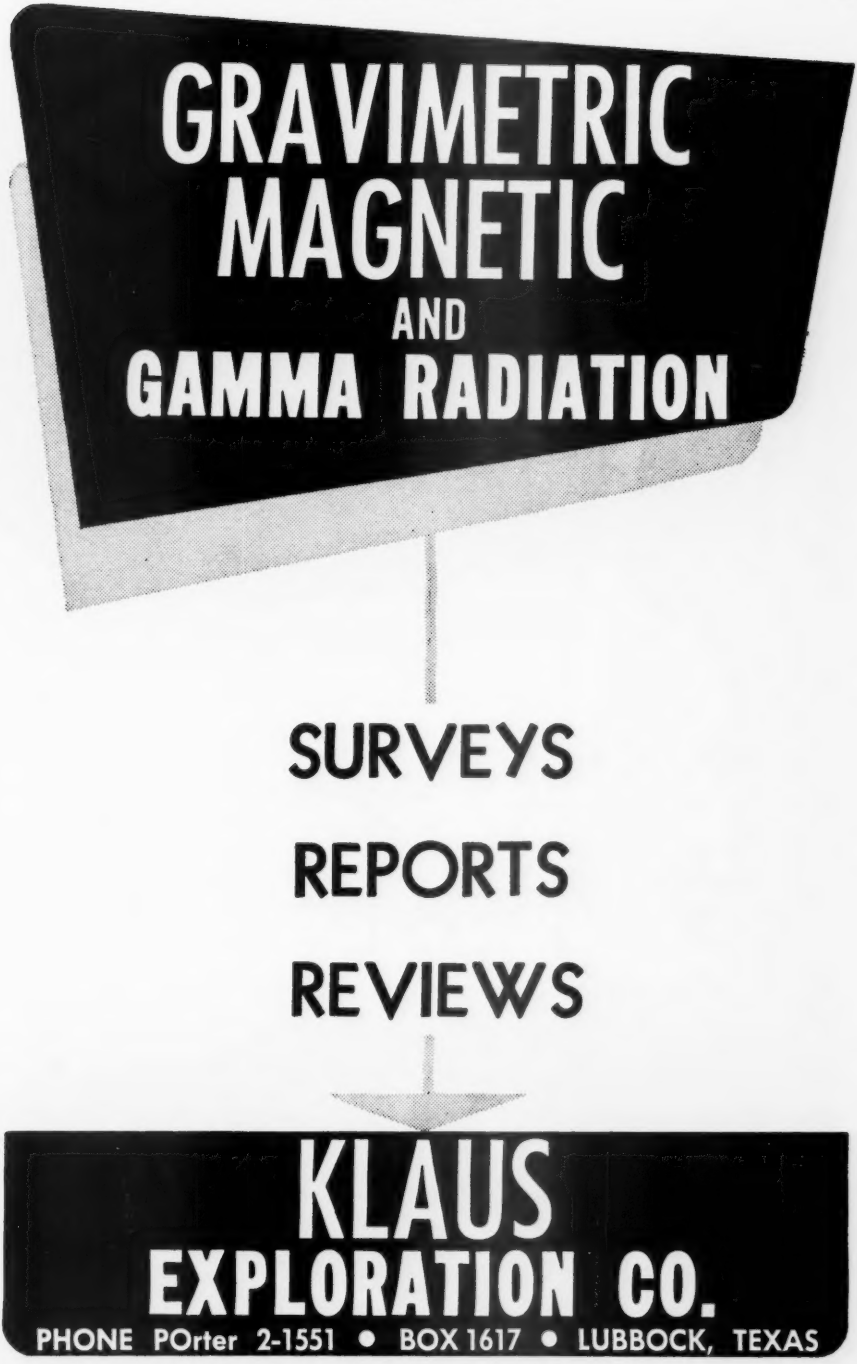
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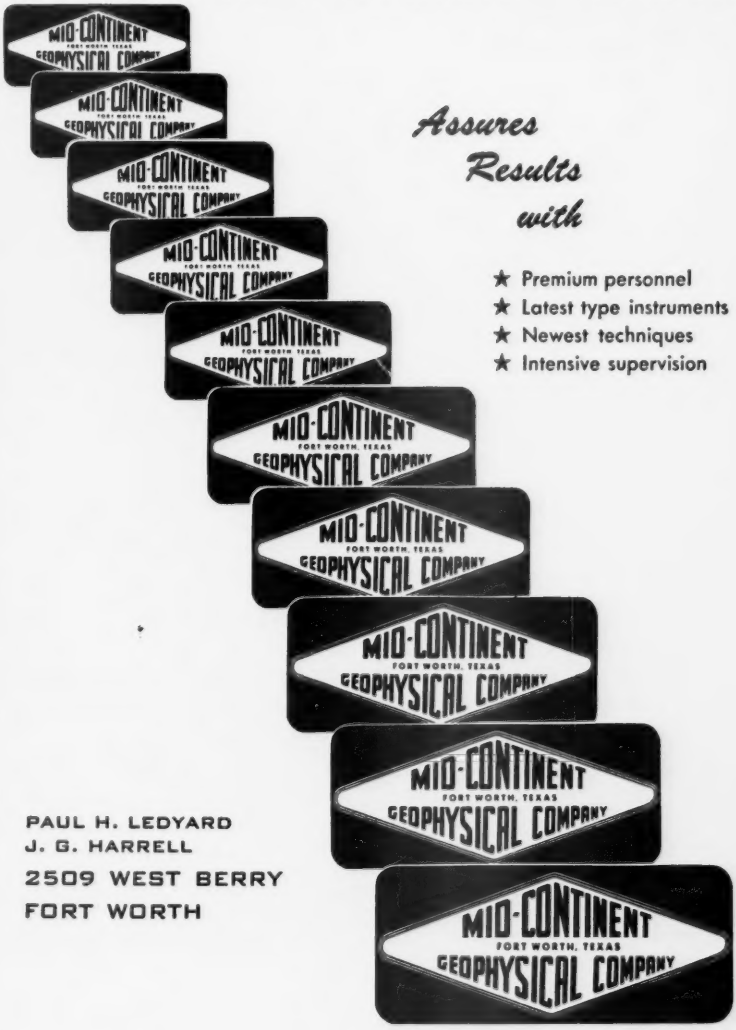

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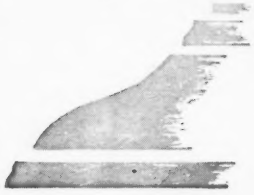

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7000 B
All Purpose Seismograph

RS-8U
Recording Oscillograph

... for shooting the entire seismic spectrum with a flip of "triggers"!

Now, with *one* seismic system (instead of three), Houston Technical Laboratories makes it possible for you to exploit every seismic method to the fullest extent.

The versatile 7000 B "All Purpose" Seismograph places the entire seismic spectrum (5-500 cps) at your fingertips . . . High Resolution Reflection Recording, Conventional Reflection Recording, and Very Low Frequency Refraction Recording. Three AGC speeds and 2975 useful filter combinations assure you of optimum instrumental control of every recording technique. The equally adaptable RS-8U Recording Oscillograph permits instantaneous change of paper speeds for the three seismic recording methods, while maintaining the highest recording accuracy and photographic quality.

Available in *portable* as well as console units, the 7000 B and RS-8U fulfill every exacting requirement for direct seismic recording. Further, their operational latitude makes these units perfect for use in magnetic operations—either field recorder and playback system, or in an office analysis system.

Write for respective bulletins—
S-309 for the 7000 B, and S-313 for the RS-8U.

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Vector Preformed Continuous Loop Takeouts help distribute strain along the entire length of the cable.

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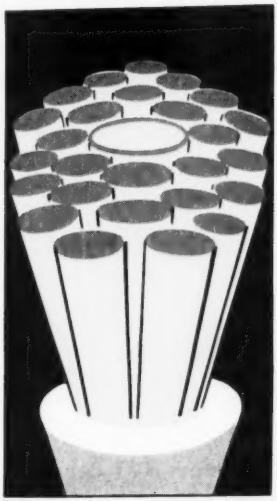

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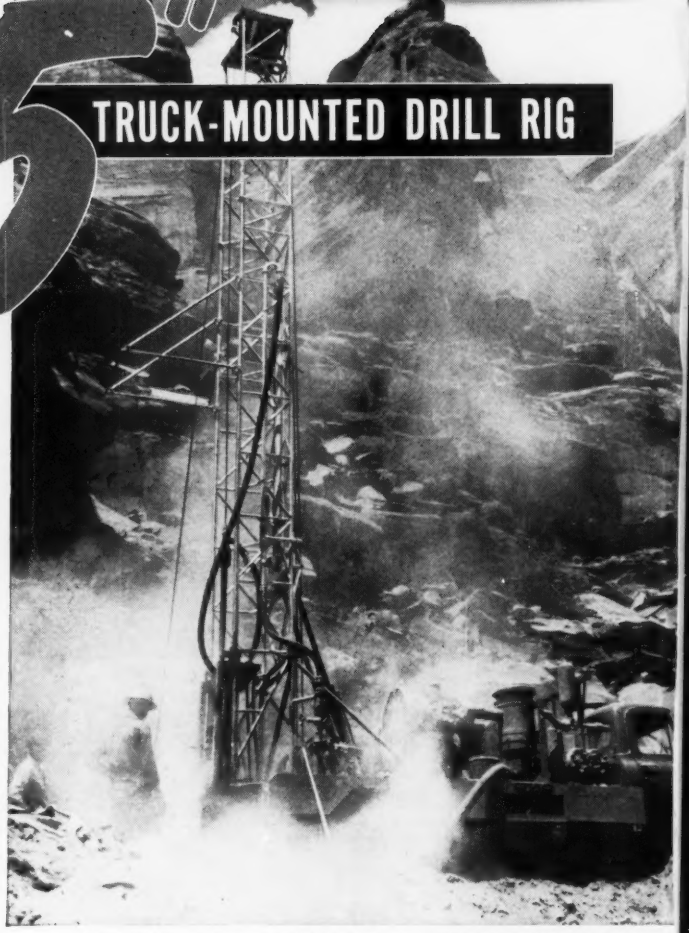

Prospecting with a Joy Model "75", equipped with both air compressor and mud pump, in the Rocky Mountains.

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All models of the "75" have features found in heavy-duty drilling equipment. Engineers with oil-country backgrounds designed the "75" with points of stress made extra strong, with extra capacity clutches, and with heavy-duty shafting and gearing. It's the ideal drill for high production, low maintenance shot hole, water well, blasthole, and core drilling.

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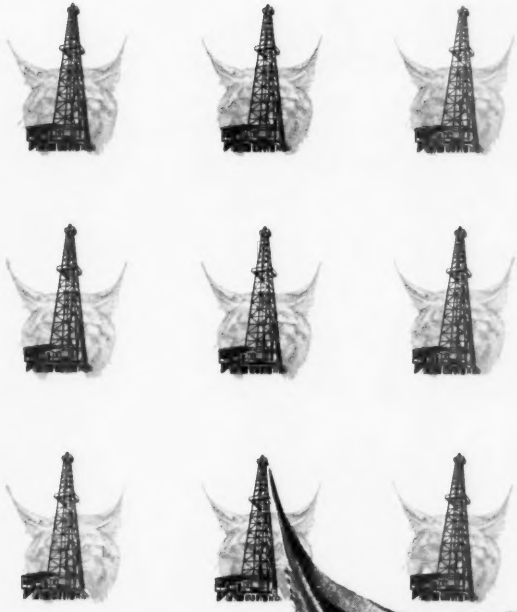

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but that wildcat could be tamed with well planned and carefully executed exploration services. This record could be bettered at least 300% if adequate geological-geophysical information were obtained beforehand. For experience, and integrity in exploration call on the Republic Exploration Company.

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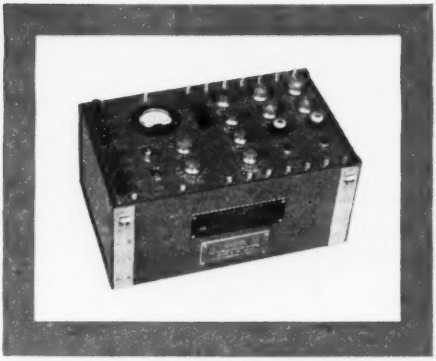
The LLI is a calibrated, voltage-measuring and voltage-indicating instrument—operative with, and a valuable supplement to, any standard seismic system. It records special PILOT TRACES on the seismograph record, with trace amplitude proportional to the logarithm of the input signal. Not to be confused with other indicating traces on some systems, the LLI operates *completely independent* of the AGC and amplifier characteristics—thus giving an accurate recording of the input voltage.

USE THE LLI TO:

- ascertain optimum arrangement in multiple seismometer array and pattern hole techniques.
- accurately measure trace unrest and ground noise level before and after the shot.
- control proper dynamite charges, filter selection, and shot depths—avoid experimenting and "over-shooting."
- compare true energy levels from record-to-record as an aid to correlation.



To learn how the LLI can benefit you, write for detailed information. Specify Bulletin No. S-302.

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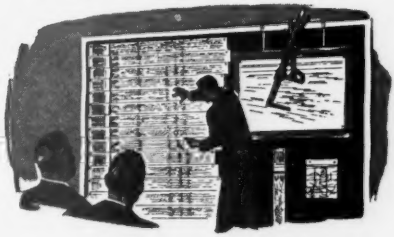

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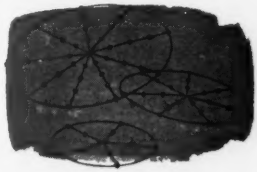
For twenty-four years, SEI has specialized in subsurface studies of the domestic oil provinces . . . from Canada to the Gulf. Numerous innovations in instrumentation, interpretation, and field technique have kept SEI in the forefront. For example, in difficult areas, SEI has been a pioneer in the use of patterns of multiple shot holes and geophone arrays.

Your exploration program is in capable hands at SEI.



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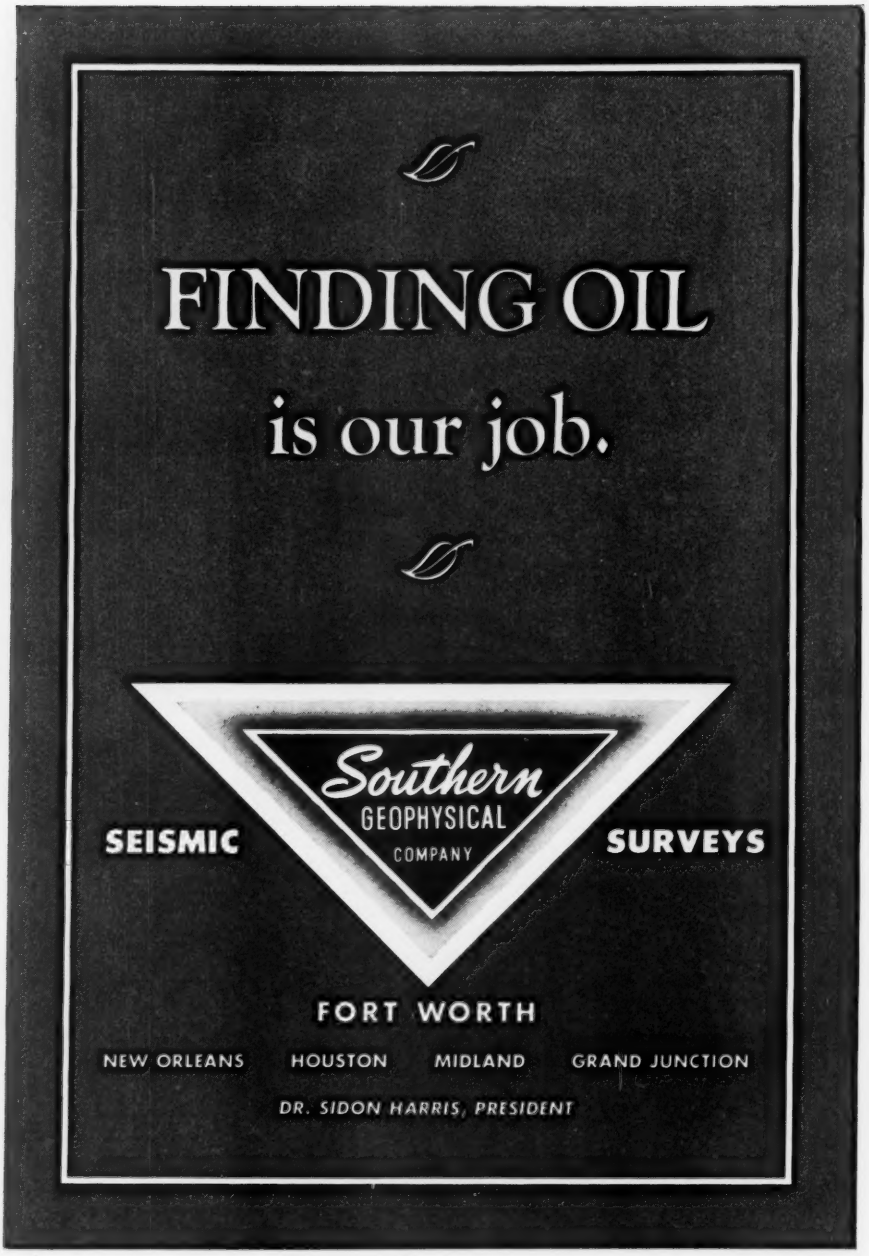
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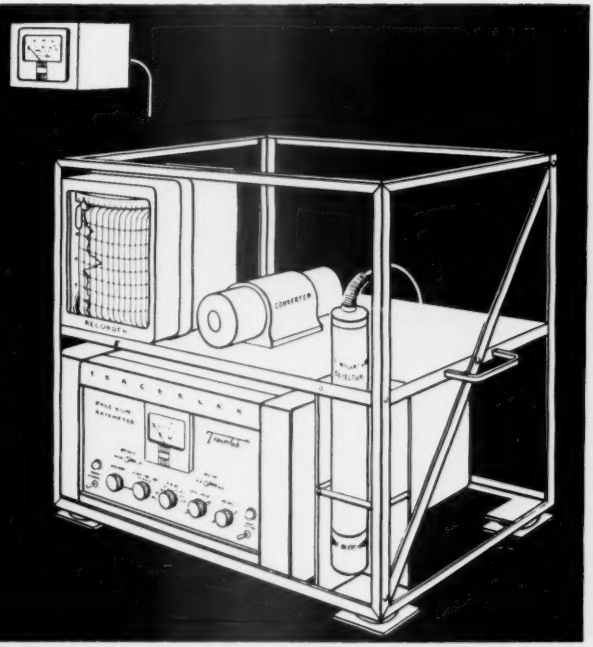

Tracerlab, the world's largest and foremost producer of nuclear equipment, manufactures precision scintillation detectors for either air- or jeep-borne reconnaissance work. These units, which are ideal for either oil or uranium prospecting, are semi-custom installations consisting of standard nuclear equipment adapted and repackaged for this application. Their design is based on extensive experience in providing custom airborne radiation equipment for special requirements.

A typical aerial surveying unit includes a sensitive scintillation detector with an extra-large gamma crystal, a precision ratemeter modified for fast response and having a wide range of counting rates, a recorder, a remote meter for use by the pilot, an alarm to signal high radiation areas, an invertor to supply necessary instrument voltage, and a 24" x 18" x 30" rack equipped with shock mounts. Other special accessories such as wing tip mounted detectors are also available.

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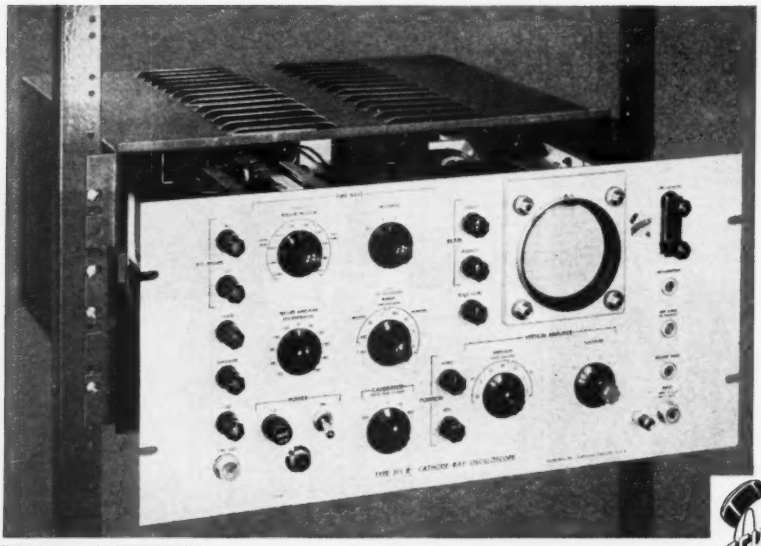

Rack-Mounting

Oscilloscope

for Geophysical Applications

TEKTRONIX®

The Tektronix Type 315R Rack-Mounting 3" Oscilloscope has many features desirable for geophysical applications. Especially useful in this field are the wide sweep range, dc to 5 mc vertical response, time and amplitude calibration accuracy, and excellent linearity of this precision oscilloscope.

One of the many applications for the Type 315R is with borehole radiation counting equipment of the pulse height discrimination type, an innovation in nuclear well logging.

MAJOR SPECIFICATIONS

Vertical Response
DC to 5 mc — 0.1 v/div to 100 v/div.
5 cycles to 5 mc — 0.01 v/div to 100 v/div.
12 calibrated steps from 0.01 v/div to 50 v/div, accurate within 3%.
Risetime — 0.07 μsec.

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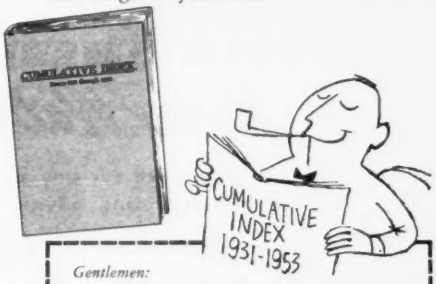

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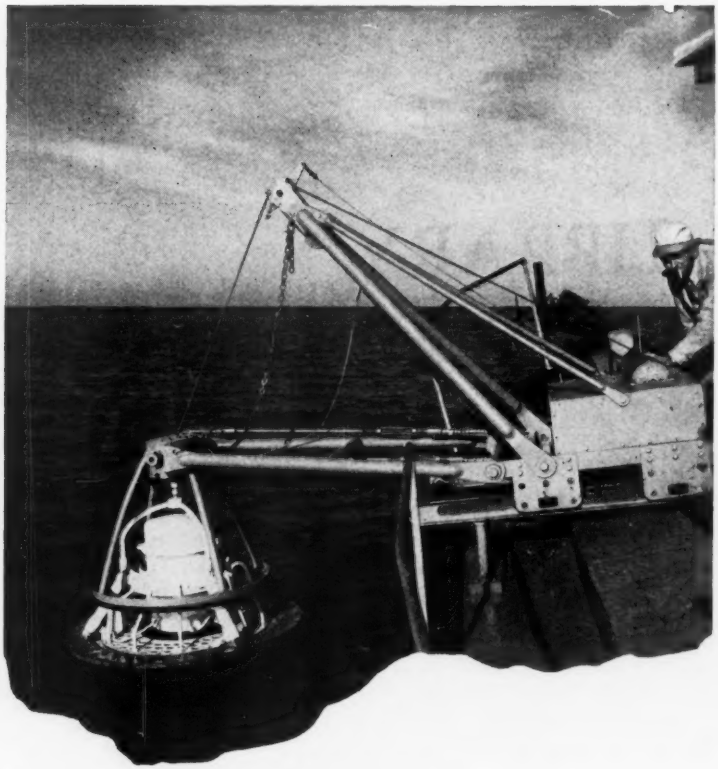

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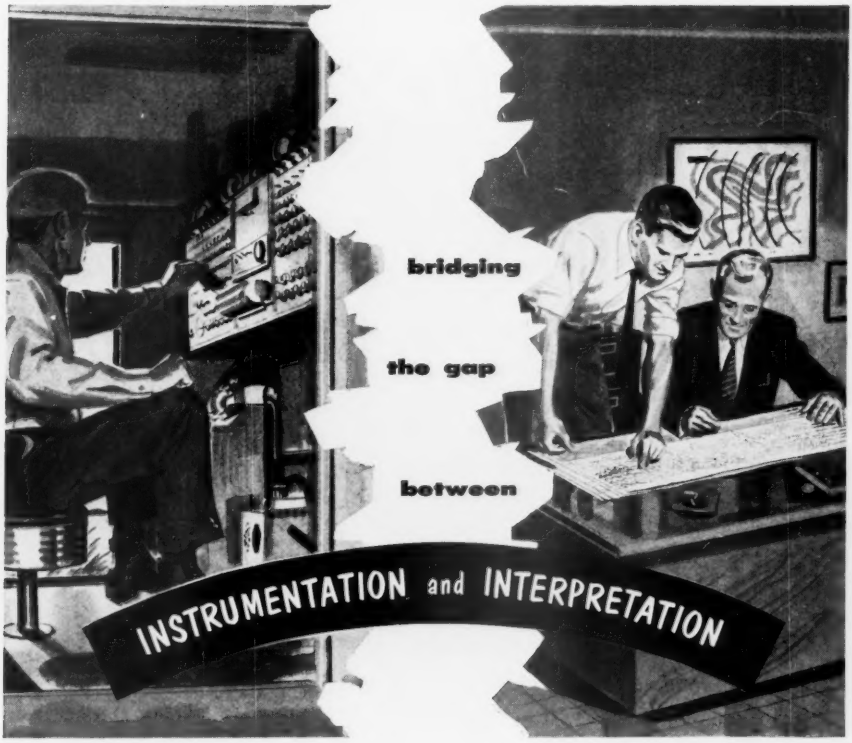

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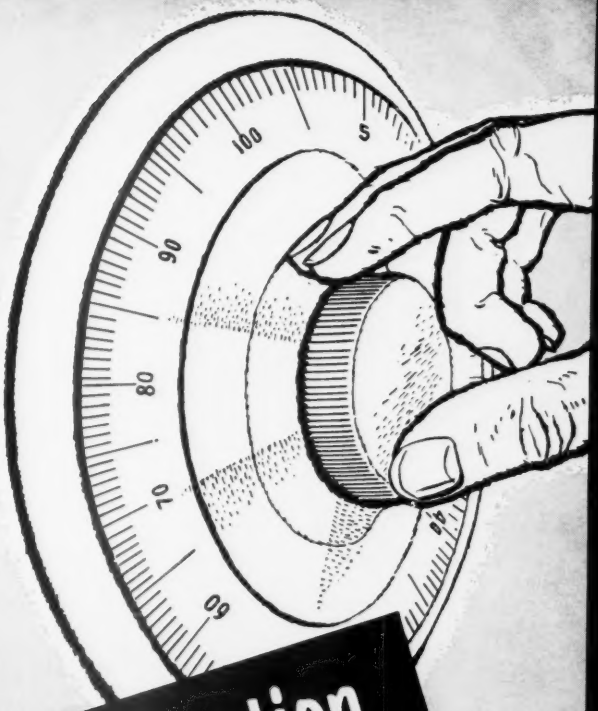

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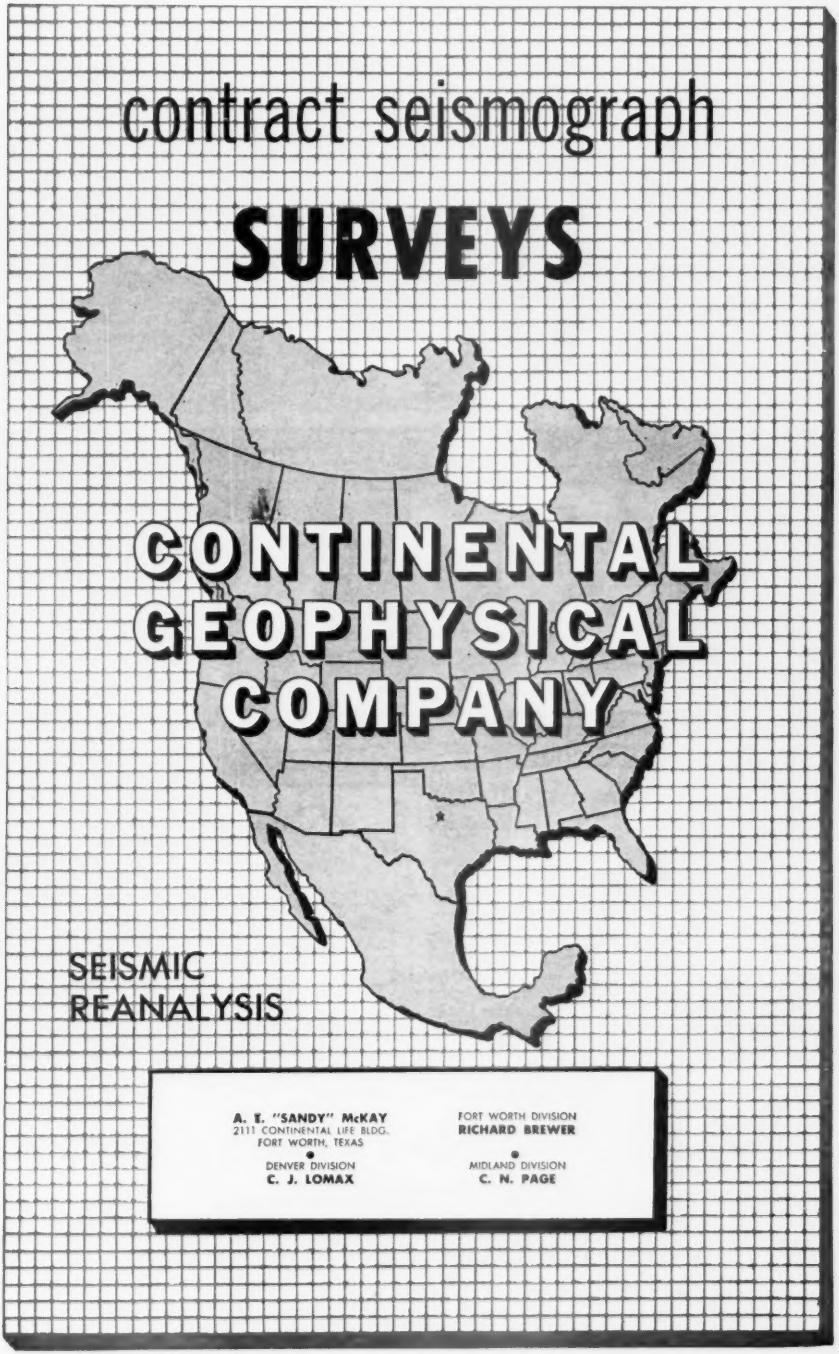

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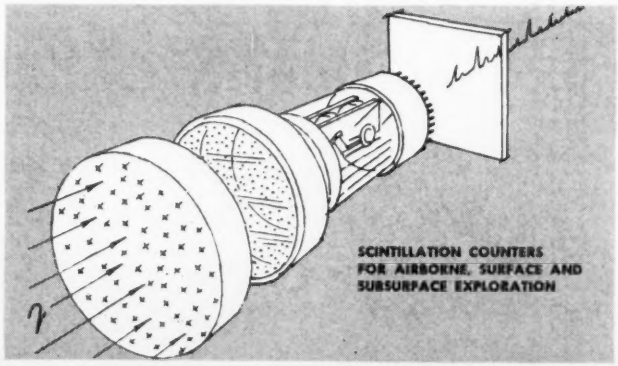

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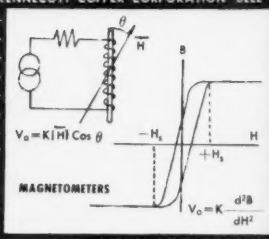

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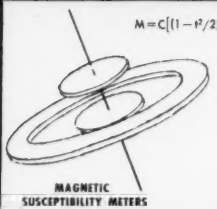

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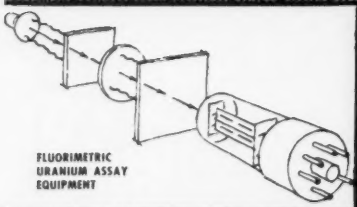

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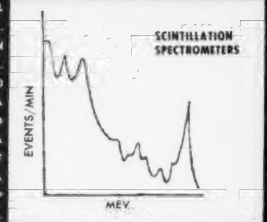

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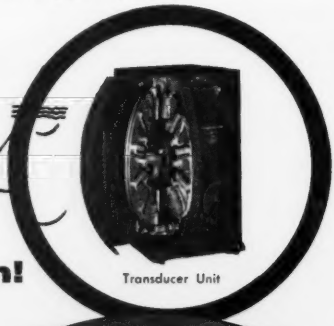

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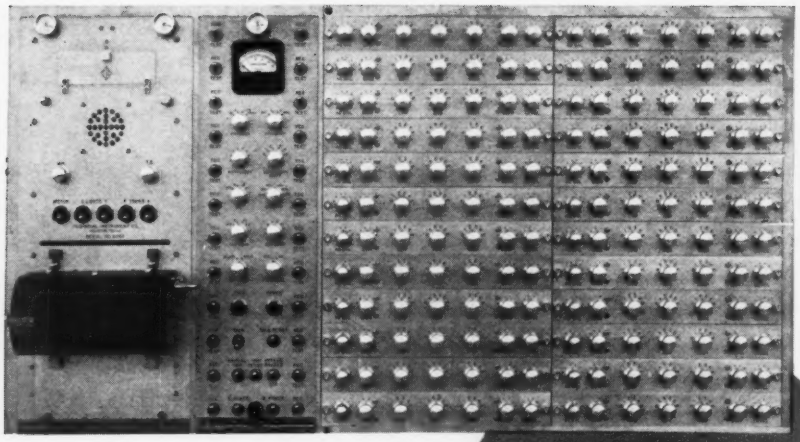

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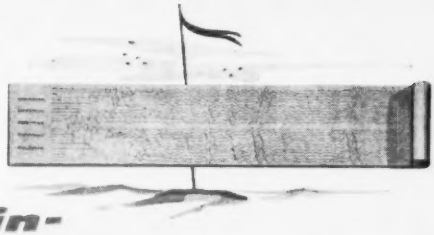

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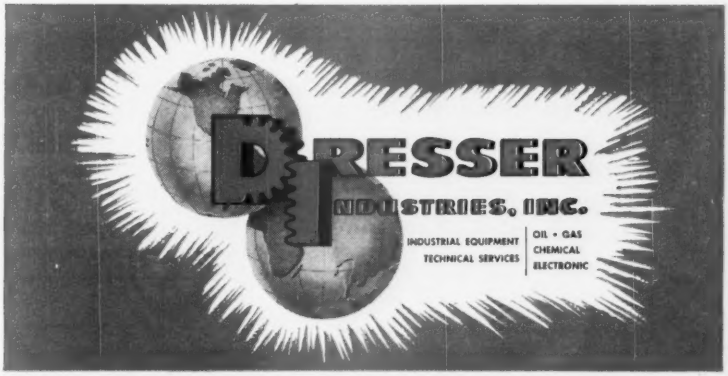

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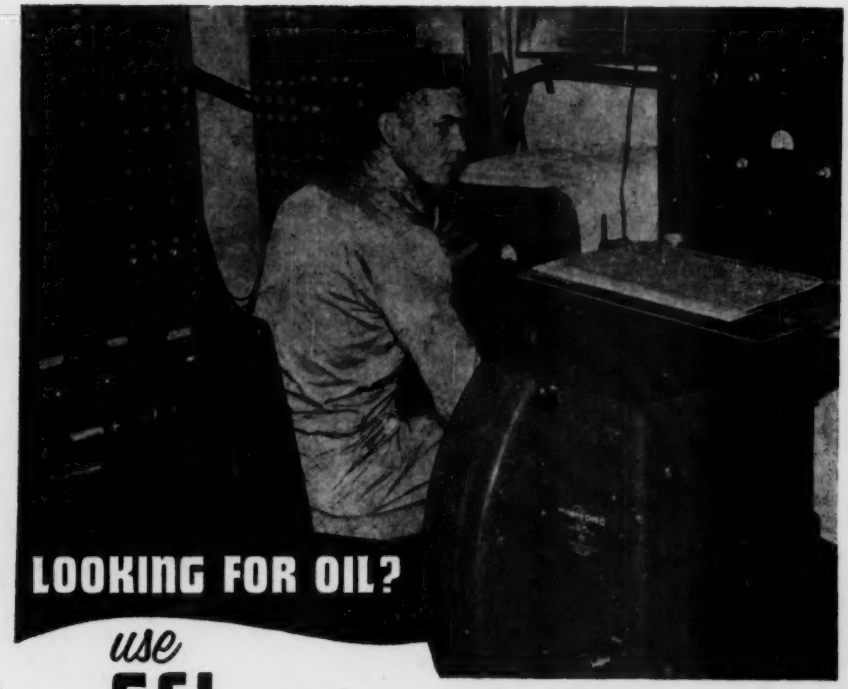

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